Project Review Committee

Each research project will have an advisory committee appointed by the LTRC Director. The Project Review Committee is responsible for assisting the LTRC Administrator or Manager in the development of acceptable research problem statements, requests for proposals, review of research proposals, oversight of approved research projects, and implementation of findings.

The dedication and work effort of the following Project Review Committee members to guide this research study to fruition are acknowledged and appreciated.

LTRC Administrator/ Manager
Chris Abadie, P.E.

Members
Philip Arena, P.E., FHWA
Mike Boudreaux, P.E., LTRC
Mark Cheeks, P.E., Beta Testing, Inc.
Craig Duos, P.E., CAAL
Mark Kelly, P.E., DOTD District 61
Khiet Ngo, P.E., DOTD Section 22

Directorate Implementation Sponsor
William H. Temple, P.E.
Chief Engineer, DOTD

TECHNICAL REPORT STANDARD PAGE

1. Report No. **FHWA-LA-06-415**	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Evaluation of Capping Systems for High-Strength Concrete Cylinders	**5. Report Date** March 2006 **6. Performing Organization Code**	
7. Author(s) John Eggers, P.E. Sadí Torres, P.E.	**8. Performing Organization Report No.**	
9. Performing Organization Name and Address Louisiana Transportation Research Center 4101 Gourrier Avenue Baton Rouge, Louisiana 70808	**10. Work Unit No.** **11. Contract or Grant No.** State Project Number: 736-99-1225 LTRC Project Number: 04-1C	
12. Sponsoring Agency Name and Address Louisiana Transportation Research Center 4101 Gourrier Avenue Baton Rouge, Louisiana 70808	**13. Type of Report and Period Covered** Final Report January 2004 – June 2005 **14. Sponsoring Agency Code**	
15. Supplementary Notes Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration		

16. Abstract

This study focused on the effects of capping systems on the compressive strength of high-strength concrete. The compressive strength levels ranged from 6,000 psi to 14,000 psi. The three systems investigated were ground ends, bonded caps, and unbonded pads. The capping compounds investigated were commercially available and advertised for testing high-strength concrete. The unbonded pads used were neoprene pads with a Shore A Durometer hardness of 70. A specialty grinding machine was used to obtain the required planeness and perpendicularity on the ground end cylinders. Statistical analyses were used to determine if any significant differences existed between the compressive strength results of the capping methods. No significant difference was found between the capping systems at the 6,000 psi, 10,000 psi, and 14,000 psi levels. However, significant differences were detected at the 8,000 psi and 12,000 psi levels. For the 8,000 psi group, ground ends produced significantly lower compressive strengths than three of the capping compounds. For the 12,000 psi group, ground ends produced significantly lower strengths than one of the capping compounds and the unbonded pads. No other clear statistical distinctions could be made from the analysis performed. In all the strength levels but the 6,000 psi level, the ground ends method produced lower compressive strengths than the rest of the methods under study.

17. Key Words high-strength concrete, capping systems, unbonded pads, ground ends	**18. Distribution Statement** Unrestricted. This document is available through the National Technical Information Service, Springfield, VA 21161.

19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified	Unclassified	96	

Evaluation of Capping Systems for High-Strength Concrete Cylinders

by

John Eggers, P.E.
Sadí Torres, P.E.

Louisiana Transportation Research Center
4101 Gourrier Avenue
Baton Rouge, Louisiana 70808

LTRC Project No. 04-1C
State Project No. 736-99-1225

conducted for

Louisiana Department of Transportation and Development
Louisiana Transportation Research Center

March 2006

ABSTRACT

This study focused on the effects of capping systems on the compressive strength of high-strength concrete. The compressive strength levels ranged from 6,000 psi to 14,000 psi. The three systems investigated were ground ends, bonded caps, and unbonded pads. The capping compounds investigated were commercially available and advertised for testing high-strength concrete. The unbonded pads used were neoprene pads with a Shore A Durometer hardness of 70. A specialty grinding machine was used to obtain the required planeness and perpendicularity on the ground end cylinders. Statistical analyses were used to determine if any significant differences existed between the compressive strength results of the capping methods. No significant difference was found between the capping systems at the 6,000 psi, 10,000 psi, and 14,000 psi levels. However, significant differences were detected at the 8,000 psi and 12,000 psi levels. For the 8,000 psi group, ground ends produced significantly lower compressive strengths than three of the capping compounds. For the 12,000 psi group, ground ends produced significantly lower strengths than one of the capping compounds and the unbonded pads. No other clear statistical distinctions could be made from the analysis performed. In all the strength levels but the 6,000 psi level, the ground ends method produced lower compressive strengths than the rest of the methods under study.

IMPLEMENTATION STATEMENT

The purpose of this study was to determine if various end conditions for testing compressive strength in concrete produce statistically significantly different test results. Louisiana Transportation Research Center will recommend that unbonded neoprene pads with 70 Shore A Durometer hardness be used for testing high-strength concrete. This will provide a more effective way of performing acceptance testing for high-strength concrete while giving more consistent results. This recommendation will be submitted as a proposed change to the Louisiana Department of Transportation and Development Testing Procedure TR 230.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

To produce accurate compressive strength test results, the condition of concrete cylinders must meet certain specifications. These specifications deal, primarily, with the end conditions of the cylinders and include requirements for perpendicularity of the ends with respect to the cylinder axis and flatness of the end surface. The test specimens prepared under field conditions likely do not meet these requirements, so some kind of end preparation becomes necessary. Various methods are available to prepare the end surfaces of the test cylinders; they range from grinding the ends to applying bonded caps such as neat cement paste and sulfur based compounds, and more recently unbonded pads such as neoprene pads confined by a rigid steel or aluminum ring *[1]*.

The need for test cylinders to meet these requirements becomes more critical for high-strength concrete (HSC). The definition of HSC changes over the years based on the applications and current practices *[2], [3], [4]*. For the purpose of this investigation, HSC will be defined as concrete with compressive strengths above 6,000 psi.

HSC usage has increased over the last 20 years. Many benefits are associated with the use of HSC, including its ability to reduce member cross sections such as slender columns and beams, thinner floor slabs, and reduced weight. Also, contractors might be able to strip formwork earlier, thus reducing the project duration.

The production of HSC requires more care in proportioning, mixing, placing, and testing than normal strength concrete *[5]*. Although HSC is very sensitive to testing errors, there is no special testing standard for testing this material *[5] [6]*. Concrete producers are concerned that the testing laboratories are not capable of properly testing high-strength concrete. To overcome this concern, the producers tend to over-design their mixtures to compensate for testing errors. This practice increases the concrete price and it is an inefficient use of materials.

There are alternatives to treat the ends of the cylinders to ensure that the load is applied uniformly when testing. One option is to grind the specimen's ends with a lapidary machine or a grinding machine, a second option is to cap the ends, and a third alternative is to use unbonded neoprene pads, which are reusable for a limited amount of tests.

Grinding the ends of the cylinder specimens with a lapidary machine is probably the preferred method of testing concrete for compressive strength. All other methods are usually compared to ground ends for verification purposes. There is no other material between the platen heads of the testing machine and the cylinder ends when a specimen is tested using this method. Another important factor is that this method is not restricted by maximum compressive strengths, as is the case with other methods. Preparing the ends of the specimen with lapidary equipment provides the perpendicularity and planeness requirements for testing, but it is time-consuming and expensive.

The ends of the specimen can also be prepared with a grinding machine that is less time-consuming than a lapidary machine but provides the perpendicularity and planeness requirements. This type of equipment can produce acceptable ends for testing in a few minutes. However, the initial cost associated with obtaining this type of equipment is a factor.

Using bonded caps on the cylinder's ends is traditionally the most common practice. This method provides a way to correct surface and perpendicularity imperfections on the test cylinders. Either high-strength gypsum plaster or sulfur mortar can be used, with the latter being the most common. The sulfur compound is melted and applied to the ends of the cylinders to fill in any imperfections and level out the surface. The maximum cap thickness is limited to approximately 0.20 in. for compressive strengths higher than 7,000 psi. A drawback to this system is that a period of time is required before the cylinders can be tested. ASTM C 617 covers the equipment and procedure involved in capping the concrete cylinders; it also requires that documentation must be provided comparing the results of cylinders with capped ends to cylinders with ground ends *[7]*.

Another common practice is to use unbonded pads. These are neoprene pads that are encased by a steel retainer ring at the ends of the concrete cylinder. The pads can be used on one end or both ends instead of caps. The main advantage of this system is that it takes less time to set up than capping compound. In addition, the pads are reusable depending on their condition after each test. The cylinders still need to meet perpendicularity requirements but the unbonded pads are allowed to be on ends with imperfections of up to 0.20 in. ASTM C 1231 limits the use of unbonded pads to cylinders with compressive strengths up to 12,000 psi. The standard requires qualification tests for cylinders with compressive strengths between 7,000 and 12,000 psi. Qualification tests for compressive strengths above 12,000 psi are not permitted with this type of system *[8]*.

OBJECTIVE

This program evaluated different capping systems used to test high-strength concrete cylinders. Some studies have indicated that a higher compressive strength is obtained with properly prepared specimens and unbonded caps, compared to capping compounds. The use of unbonded pads is limited by testing standards that require comparing their results to ground end specimens for validation. The purpose of this investigation was to determine which capping system provides higher compressive strength results with less variability. In order to do this, cylinders of various high-strength concrete mixes were made and tested for compressive strength using different capping systems. The outcome of this investigation can later be used by state and local agencies to address the verification of high-strength concrete compressive strength.

Since the current bridge and paving specifications are moving towards high-performance and high-strength concrete, a better understanding of how the capping systems affect the tests results is needed. This will provide the base for developing test procedures to be included in Quality Control and/or Quality Assurance programs. This study will help in understanding which capping systems will provide the best representation of the actual high-strength concrete being used in a particular project.

SCOPE

The first task for this investigation was to perform a literature review to survey previous work conducted by other researchers.

The specimen size selected for this study was limited to 6 by 12 in. cylinders. The cylinder end conditions studied were ground ends, four high strength sulfur based capping compounds, and unbonded neoprene pads. The ground end cylinders were used as control specimens to compare the results with the capping compounds and the unbonded pads. The strength levels selected for this investigation ranged from 6,000 psi up to 14,000 psi in increments of approximately 2,000 psi.

A statistical analysis of the results was performed in an effort to correlate the end condition to the compressive strength of the concrete.

METHODOLOGY

Literature Review

The standard capping method in the 1920s was neat cement paste. Gonnerman investigated alternatives to this method. The concrete studied in this investigation ranged from 1,000 to 5,500 psi. The methods studied included gypsum and mixtures of gypsum and portland cement that produced results similar to neat cement paste caps. Alternative unbonded sheet materials were also investigated, but they produced lower strengths. The reduction in strength was higher as the concrete strength increased *[9]*.

A sand cushion method was investigated in 1926 by Purrington and McCormick. Sand was placed inside a confining ring with a diameter of 6 ½ in. Comparative studies reported that the strength obtained with this method was comparable to cylinders with cement paste caps *[10]*.

Freeman provided information on the use of sulfur mortar in 1928. This method used a horizontal capping device while the current practice uses a vertical device *[11]*. In 1930 Freeman reported that this material produced better results than other types of systems *[12]*. By 1939, the use of sulfur mortar was common practice in many laboratories *[13]*.

An early 1940s study involving end treatments for testing concrete cylinders tested 8,000 psi concrete with different materials used on the ends of the cylinders. The end conditions of the concrete cylinders before capping were studied: these were plane ends normal to the axis of the cylinder, plane ends not normal to the axis of the cylinder, convex ends, and concave ends. The end conditions were selected to simulate field conditions. The use of a gypsum compound and a sulfur-silica compound gave higher strengths and a greater degree of uniformity when compared to other methods such as plaster of Paris and steel shot in dry and oiled conditions. Using the gypsum compound provided a slight increase in performance *[14]*.

A 1944 study found limitations of testing with sulfur based compounds. The cylinders did not develop their full strength potential due to the curing of the caps. This study compared same day testing and next day testing. The average thickness of the caps was measured at 1/4 in. The results showed that thinner caps increased the compressive strength. Based on the findings, the study recommended making the sulfur caps as thin as possible *[15]*.

One of the conclusions reported by Werner in 1958 was that the use of different capping materials had a greater effect on the high-strength concretes than the low-strength concrete. High-strength concrete cylinders with rough ends resulted lower strength than companion cylinders with smooth ends. The surface condition effect produced negligible effects on the low-strength concrete. Also, thicker sulfur caps produced a 5 percent reduction in strength *[16]*.

A study comparing concrete compressive strengths between unbonded neoprene pads and sulfur compound capping led to the following conclusion: the strengths with neoprene seemed to be higher, although the magnitude of the difference was negligible. Also the testing variation associated with neoprene pads is no higher than that associated with sulfur caps. Since neoprene pads are reusable to certain extent, these are less costly and time consuming than sulfur caps. The use of neoprene pads does not expose technicians to harmful vapors, as compared to sulfur caps. The concrete compressive strength for this study was less than 6,000 psi, and the neoprene pads used were 1/2 in. thick with a 50-durometer hardness *[17]*.

Carasquillo and Carrasquillo, 1988, compared two systems of unbonded pads and a high strength sulfur mortar. One of the unbonded systems (aluminum rings), when compared to the sulfur mortar showed an average 3 percent reduction in compressive strength between the 4,000 and 10,000 psi range. Above this range, the unbonded aluminum pads produced strengths an average of 9 percent higher than the sulfur mortar. The steel ring system presented a similar case, with less than a 1 percent reduction in compressive strength when compared to sulfur mortar for the 4,000 to 10,000 psi range. For the range above 10,000 psi, two cases were reported to have produced substantially higher strengths than the sulfur mortar. The authors provide two possible explanations for these occurrences; the inadequacy of the sulfur mortar to develop the full strength of the concrete and lateral constraint provided by the unbonded pad when it squeezes out of the retaining ring. They also found differences in the compressive strength using two sets of retaining rings from the same manufacturer. Additionally, sulfur caps and unbonded pads produced similar strength results. The unbonded pads were reported in some cases as having lower variability than sulfur caps *[18]*.

Lessard et al. (1993) suggested that in only two cases is it necessary to grind the ends of the cylinders—1) when high accuracy is required for concrete below 18,855 psi, given that a high quality capping compound with cube strengths between 7,250 and 8,700 psi is used, and 2) when the compressive strength of the concrete exceeds 18,855 psi. However, they recommend that specimens that might exceed 14,500 psi should be ground. Their study did not find significant differences between ground ends and capped specimens' compressive strength. The ground ends specimens had a lower coefficient of variance compared to the capped specimens. Also, a capping thickness of 1/16 to 1/8 in. is recommended for high strength concrete *[19]*.

Another comparison study between sulfur caps and unbonded polymer pads found that the sulfur caps can lead to a higher scatter in the measurement of compressive strength of high-strength concrete. The results show that higher within-test variability was found using sulfur caps than using the unbonded polymer pads. Ground ends cylinders produced less variable results for compressive strengths of 10,000 psi and higher *[20]*.

The authors did not find a significant difference between sulfur caps and unbonded polymer pads in 6 by 12-in. cylinders up to strengths of 8,000 psi [7]. Also, they did not find any significant difference in 4 by 8-in. cylinders up to strengths of 13,000 psi. Above these levels, the strengths obtained using unbonded pads were higher. They recommended that end surfaces should be ground for testing concretes above 10,000 psi. Special care must be taken in preparing the ends of the specimens, so that they do not produce poor results. This should be done for both sulfur caps and unbonded polymer pads for consistency of results. They recommend grinding the cylinder ends to a planeness of 0.001 in. and 0.3 degrees of perpendicularity *[20]*.

Another system for testing HSC has been developed in France. It uses two steel boxes similar to the ones used for unbonded pads, which are filled with sand. Then a paraffin seal is applied between the cylinder and the box to confine the sand in the box and provide good centering of the specimen within the box. This method seems to produce results that are about 5 percent lower than using ground ends cylinders *[21]*.

French and Mokhtarzadeh compared three end conditions: ground ends, unbonded pads, and high-strength sulfur compound in concretes with strengths over 14,500 psi. It was reported that ground ends produced strengths about one percent higher than sulfur caps. For strengths between 7,000 and 12,000 psi, the unbonded pads produced slightly higher strengths than the ground ends *[22]*.

In 1994, Carino et al. investigated the effects of different variables on concrete cylinder strength. The variables studied were end preparation, cylinder size, type of testing machine, and nominal stress rate. It was reported that the ground end cylinders produced strengths an average of 2.1 percent higher than sulfur caps. However, the ground ends produced up to 6 percent higher strength than the sulfur caps for the 13,000 psi concrete, suggesting a significant effect due to the interaction of strength and end condition *[23]*.

A comparison study between sulfur mortar, cement paste, and ground ends found that cylinders with sulfur mortar caps tested 2 to 4 hours after cap preparation resulted in lower measured strengths. The reduction in strengths was between 2-3 percent with 1/16 in. thick caps and 5-7 percent reduction with cap thickness of 3/16 in. There was no significant difference between sulfur mortar when applied 6 to 7 days before testing. This study showed that the sulfur caps can be used to test high-strength concrete if the cap thicknesses are limited and sufficient time is allowed for the cap to gain strength before testing *[24]*.

Another study by Vichit-Vadakan, Carino, and Mullings suggested that the cube compressive strength of the compound may not be as important as its modulus of elasticity. A higher modulus value will yield better results *[25]*.

Burg, Caldarone, Detwiler, Jansen, and Willems suggested that capping compounds should not be used in concretes with compressive strengths above 10,000 psi, unless a comparative analysis has been made between the capping compound and ground end cylinders *[26]*.

The American Concrete Institute Guide to Quality Control and Testing of High-Strength Concrete recommends that when capping is used for testing the compressive strength of high-strength concrete, it should comply with the requirements of ASTM C 617. Sulfur capping compounds with cube compressive strengths of 8,000 -10,000 psi are suitable to test concrete cylinders with compressive strengths up to 10,000 psi. It also recommends not exceeding 1/16 in. as the maximum thickness of the capping material *[27]*.

A small scale test program by FHWA's Mobile Concrete Laboratory (MCL) did not find significant differences in compressive strength tests between sulfur caps and neoprene pads. Significant differences were detected between ground ends and bonded caps, and unbonded pads. It was reported that grinding the ends of the specimens led to a reduction in compressive strength of 15 percent compared to the other capping systems. Also, variability was reported to be higher for the ground ends, approximately twice the variability of the unbonded pads *[28]*.

Preliminary Testing

Capping Compounds

Four sulfur based capping compounds were tested to determine their compressive strength. Three of the tested compounds were commercially available at the time of testing; the fourth compound is not commercially available anymore. All of the compounds were advertised for use with high-strength concrete. The procedure described in ASTM C 617, Standard Practice for Capping Cylindrical Concrete Specimens, was followed to determine the compressive strength of cubes made out of capping compound.

Concrete

It was determined that 15 specimens per end condition would provide a sample size large enough to perform statistical analyses. Having 15 samples with a significance level of 0.05 and a standard deviation of 400 psi allowed the investigators to detect a difference of approximately 200 psi between the test hypotheses. Previous research data have established that a standard deviation of 400 psi is achievable for high-strength concrete in the laboratory environment.

Concrete Mixtures

Concrete mixtures for five strength levels were designed to study the effect of the different end conditions on the strength of the concrete cylinders. The goal was to produce concrete cylinders which mean compressive strengths ranging from 6,000 psi up to 14,000 psi with intervals of 2,000 psi within consecutive strength levels.

Materials

Commercially available portland cement Type I was used for all the batches. The fine aggregate was a natural Louisiana sand meeting ASTM C33 fine aggregate grading requirements. The coarse aggregate was crushed limestone meeting an ASTM C33 Size Number 67 grading (3/4 in. maximum nominal size). An additional intermediate aggregate was used in all batches except for the 6,000 psi group. The purpose of the intermediate aggregate was to produce a denser concrete by reducing the amount of paste. Crushed peagravel with a maximum aggregate size of 1/2 in. was used for the 8,000 psi batches. In the batches for the 10,000 psi to 14,000 psi groups, a limestone meeting requirements for ASTM C33 Size Number 8 (3/8 in. maximum nominal size) grading was used as the additional aggregate. Mixture proportions are shown in table 1.

The water to cement ratios were reduced accordingly to produce higher strengths. A high range water reducer was used to aid the workability and compensate for the low water to cement ratios. Different mixture proportions were developed for all strength levels except for the 12,000 and 14,000 psi ranges. The difference between these two mixtures was the age at which they were tested; additional time was required for the 14,000 psi to develop the target strength. The concrete mixtures were not specifically designed to obtain the target strength at 28 days of age. For this reason, additional cylinders were made from each batch to monitor strength development and ensure the compressive strength was within the desired range. Once these cylinders reached the target strength, the rest of the cylinders in that batch were tested. The concrete age at testing is presented in table 1, which shows that the testing age varied between different strength levels. All the batches for a strength level were tested at the same age.

Casting and Curing

Twenty five concrete batches were prepared to obtain the required number of test specimens. All the mixing was performed in a 6 cubic foot stationary mixer. The specimens were cast as 6 by 12 in. cylinders. Plastic molds were used following the procedure described in ASTM C 192. Approximately 21 cylinders were prepared from each batch, providing three specimens for each of the six end conditions and leaving the extra cylinders to verify the target strength. This casting scheme provided 15 cylinders for each end treatment in each strength level.

The specimens were undisturbed for a minimum of 20 hours before stripping. Then the specimens were placed in a 100 percent humidity room where they were kept long enough to obtain the target compressive strength. Curing time varied from 22 days to 57 days depending of the strength development rate of the concrete cylinders.

Table 1
Mixture proportions table

	Mixture Identification				
	6,000	**8,000**	**10,000**	**12,000**	**14,000**
w/c	0.45	0.40	0.29	0.25	0.25
Cement, lbs/yd^3	508	575	1,000	1,000	1,000
Water, lbs/yd^3	228	224	290	250	250
Coarse Aggregate, lbs/yd^3	1,965	1,808	974	920	920
Intermediate Aggregate, lbs/yd^3	0	494	844	920	920
Fine Aggregate, lbs/yd^3	1,385	985	914	1,040	1,040
High Range Water Reducer, oz/cwt	4	6	8	8	8
Slump, in	3.00	3.50	4.50	4.25	8.00
Air Content, %	2.60	2.30	2.40	2.00	1.40
Unit Weight, lbs/ft^3	149.90	150.50	147.80	154.00	153.80
Testing Age, days	49	49	28	22	57

Preparation of Cylinder Ends

To keep variations between batches from affecting one particular end condition, the test specimens were randomly distributed in groups according to the number of end conditions to be examined. Table 2 presents the arrangement used to distribute the test specimens in groups; a total of 450 compressive strength tests results were used to determine differences between end conditions.

Table 2
Arrangement used to distribute test samples among capping systems

Batch No.	Strength Level (psi)	Ground Ends	Capping Comp A	Capping Comp B	Capping Comp C	Capping Comp D	Unbonded Pads	Cylinders per Batch
1	6,000	3	3	3	3	3	3	**18**
2	6,000	3	3	3	3	3	3	**18**
3	6,000	3	3	3	3	3	3	**18**
4	6,000	3	3	3	3	3	3	**18**
5	6,000	3	3	3	3	3	3	**18**
6	8,000	3	3	3	3	3	3	**18**
7	8,000	3	3	3	3	3	3	**18**
8	8,000	3	3	3	3	3	3	**18**
9	8,000	3	3	3	3	3	3	**18**
10	8,000	3	3	3	3	3	3	**18**
11	10,000	3	3	3	3	3	3	**18**
12	10,000	3	3	3	3	3	3	**18**
13	10,000	3	3	3	3	3	3	**18**
14	10,000	3	3	3	3	3	3	**18**
15	10,000	3	3	3	3	3	3	**18**
16	12,000	3	3	3	3	3	3	**18**
17	12,000	3	3	3	3	3	3	**18**
18	12,000	3	3	3	3	3	3	**18**
19	12,000	3	3	3	3	3	3	**18**
20	12,000	3	3	3	3	3	3	**18**
21	14,000	3	3	3	3	3	3	**18**
22	14,000	3	3	3	3	3	3	**18**
23	14,000	3	3	3	3	3	3	**18**
24	14,000	3	3	3	3	3	3	**18**
25	14,000	3	3	3	3	3	3	**18**
	Totals :	**75**	**75**	**75**	**75**	**75**	**75**	**450**

Ground Ends

A specialty cylinder end grinding machine was used to obtain the required planeness and perpendicularity as per ASTM C 39 on the ground end cylinders. A photo of the grinding machine is shown in figure 1. This machine has a vise that holds the specimen in place while a grinding wheel moves from side to side removing material from the specimen. Once the first end is ground, the vise is rotated 180 degrees to allow grinding on the other end. The cylinder is not removed from the vise until both ends are ground. This configuration ensures that both ends of the cylinder are parallel to each other. Figure 2 shows the configuration of the grinding system. The preparation of the cylinder ends with this type of equipment is not as time consuming as the preparation needed by lapping methods. Approximately 20 minutes were required for the preparation of both cylinders' ends. Some advantages of this method are that the cylinders can be tested as soon as the ends are ground, and the laboratory technicians are not exposed to harmful vapors. This method can also be used with unbonded pads when the cylinder's ends do not meet the specification requirements. The cylinders with ground ends were used as control specimens to compare with the other systems.

Figure 1
View of the grinding machine used in this project

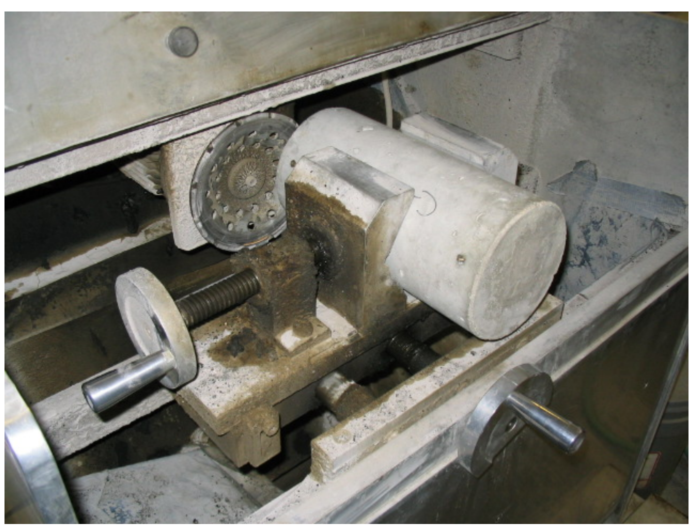


Figure 2
Close up of the vise and grinding wheel

Capping Compounds

The capping compounds were applied to the cylinders approximately 20 hours before testing the specimens. This extended period of time allowed the caps to develop sufficient strength before testing. Individual melting pots were assigned to each capping compound to facilitate their application and to avoid accidental contamination with other compounds; these are shown in figure 3. Caps were checked for perpendicularity after the compound was applied. Caps not meeting perpendicularity or planeness requirements were removed and replaced. Once applied, the capping material was used only one time; no re-melted capping material was used for end preparation. The procedure described in ASTM C 617 was followed for the preparation of the bonded caps. Figure 4 presents cylinder specimens with caps ready to be tested, three of the capping compounds are represented here.

Figure 3
Individual melting pots were used for each capping compound to eliminate contamination, capping devices are also shown

Unbonded Pads

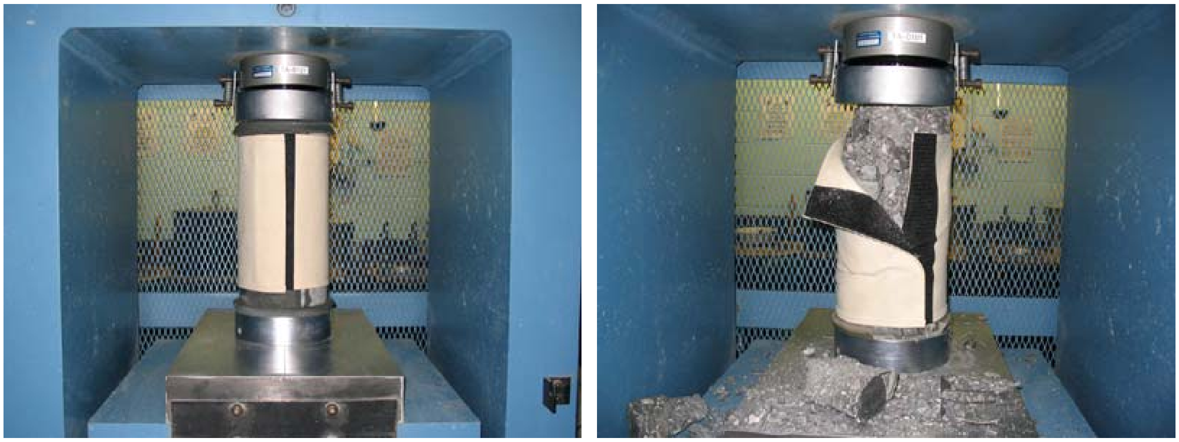
The unbonded pads used were neoprene pads with a Shore A Durometer hardness of 70. Figure 5 shows one of the pads and steel rings used during testing; the steel rings used were machined from a solid steel piece. The steel retaining rings and neoprene pads were in compliance with ASTM C 1231. The cylinders were checked for planeness and perpendicularity requirements as specified in ASTM C 1231. Severe deformation of the neoprene pads was observed when testing the higher strength levels. In some cases the pads did not last as long as they would usually last when testing normal-strength concrete.

Figure 4
Concrete specimens with capping ready to be tested in compression, the specimens in the back were tested using unbonded pads

Figure 5
Rubber pads and steel rings used for the unbonded pads tests

Compression Testing

The testing of concrete cylinders was performed on a servo-controlled compression testing machine with a maximum load capacity of 600,000 pounds. The frame rigidity on this machine exceeded ACI recommendations for minimum longitudinal stiffness *[27]*. The specimens were loaded until failure at a load rate of 60,000 pounds per minute. Testing followed the procedure in ASTM C 39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. Figure 6 presents a cylinder with capping compound before and after testing.



(a) **(b)**

Figure 6

(a) Cylinder specimen with bonded caps ready to be tested in compression, the wrapping around the cylinder helps in confining the particles that may fly off the sample; it does not affect the strength resistance of the specimen, (b) cylinder after testing

DISCUSSION OF RESULTS

The test results were analyzed using statistical methods to correlate the compressive strength with the different cylinder end conditions tested and monitor any variation in compressive strength between batches. The statistical methods included, but were not limited to the recommendations of ACI Manual of Concrete Practice 214R, Evaluation of Strength Test Results of Concrete.

Capping Compound Compressive Strength Tests

The strength of the capping compounds was determined by testing 2 in. cubes. The cubes were tested at approximately 20 hours of age to match the age of the caps on the cylinders. The average cube strengths ranged from 8,560 to 10,760 psi. The average results of the nine cubes that were tested for each compound are presented in table 3. The coefficients of variance for the compounds are also shown in table 3. Capping Compound B exhibited less variability than the other compounds.

An Analysis of Variance (ANOVA) was performed on the data to determine if any significant difference existed between the capping compounds. The analysis indicated that a significant difference did exist between the compounds at the 95 percent confidence level. The post-ANOVA tests (Tukey) indicated that Compound B had a higher compressive strength than compounds A and D. No other clear distinction could be made between the capping compounds. The results of the post-ANOVA test are presented in table 3.

Table 3
Compressive strength for capping compounds

Capping Compound Id.	Mean Compressive Cube Strength (psi)	Tukey's Grouping	Coefficient of Variance
B	10,760	A	3.17%
C	9,960	B A	8.71%
A	9,280	B C	10.92%
D	8,560	C	8.33%

Concrete Compressive Strength Tests

Data overview

The compressive strength results were grouped together by end conditions for each strength level, and the statistical parameters such as mean, standard deviation, and coefficient of variance were determined. The statistical parameters of the compressive strength tests data is presented in table 4. For all strength levels but the 6,000 psi group, the ground ends produced lower compressive strengths than the other methods. For the 6,000 psi, 8,000 psi, and 10,000 psi groups the highest compressive strengths are produced by bonded caps. Capping C produced the highest strength at the 6,000 psi level. At the 8,000 psi level, the highest strength was produced by Capping D, while Capping A produced the highest compressive strength at the 10,000 psi level. For the 12,000 psi and 14,000 psi groups, the unbonded pads produced higher compressive strength results than the other capping methods.

The plot of the compressive strength means for the end conditions by strength level shows some variability as the strength level increases, but there seems to be no apparent trend as far any end condition that gives the higher compressive strength in all the levels investigated. For all strength levels except the 6,000 psi group, the ground ends produced the lower compressive strengths. Figure 7 presents a graphical comparison of the mean compressive values for the different end conditions grouped by strength level. Figure 7 shows that as the strength level increases, the compressive strength produced by the end conditions have more variability.

Figure 8 presents a comparison of coefficients of variance for each end condition grouped by compressive strength level. This arrangement shows that small variations are found at the 6,000 psi and 10,000 psi strength levels. At these levels, the coefficient of variance for the unbonded pads is either very similar to the coefficient of variance for the ground ends. The coefficient of variance tends to increase as the compressive strength of the specimens increase; however, the 8,000 psi group does not seem to follow this trend. This behavior can be explained by looking into the 8,000 psi group and its compressive strengths when grouped by batches.

Table 4
Statistical properties for all data

End Conditions	Mean (psi)	Std Dev (psi)	Coeff. of Variance	Min (psi)	Max (psi)	Range (psi)	N
6,000 psi Group							
Ground	6,333	199	3.14%	6,090	6,860	770	15
Capping A	6,314	316	5.00%	5,880	6,970	1,090	15
Capping B	6,321	149	2.36%	6,060	6,570	510	15
Capping C	6,411	263	4.10%	5,920	6,830	910	15
Capping D	6,319	220	3.48%	5,860	6,730	870	15
Unbonded	6,385	218	3.41%	5,810	6,650	840	15
8,000 psi Group							
Ground	7,313	724	9.90%	5,440	8,100	2,660	15
Capping A	7,687	422	5.49%	6,860	8,270	1,410	15
Capping B	7,603	554	7.29%	6,580	8,420	1,840	15
Capping C	7,676	530	6.90%	6,490	8,280	1,790	15
Capping D	7,772	467	6.01%	7,070	8,600	1,530	15
Unbonded	7,608	412	5.42%	7,010	8,370	1,360	15
10,000 psi Group							
Ground	10,545	362	3.44%	9,790	11,060	1,270	15
Capping A	10,956	390	3.56%	10,400	11,780	1,380	15
Capping B	10,652	455	4.27%	9,770	11,580	1,810	15
Capping C	10,653	364	3.42%	10,010	11,270	1,260	15
Capping D	10,680	294	2.75%	10,310	11,310	1,000	15
Unbonded	10,840	330	3.04%	10,340	11,370	1,030	15
12,000 psi Group							
Ground	12,601	927	7.36%	10,800	14,220	3,420	15
Capping A	13,435	397	2.96%	12,890	14,100	1,210	15
Capping B	13,023	589	4.52%	11,810	13,740	1,930	15
Capping C	13,548	342	2.52%	12,930	14,290	1,360	15
Capping D	13,000	826	6.36%	10,960	14,110	3,150	15
Unbonded	13,599	567	4.17%	12,680	14,690	2,010	15
14,000 psi Group							
Ground	13,414	1,327	9.89%	10,610	15,030	4,420	15
Capping A	14,255	898	6.30%	12,830	15,730	2,900	15
Capping B	14,015	1,499	10.70%	9,080	15,250	6,170	15
Capping C	14,250	1,126	7.90%	12,560	15,500	2,940	15
Capping D	14,131	866	6.13%	12,650	15,430	2,780	15
Unbonded	14,511	706	4.87%	13,480	15,740	2,260	15

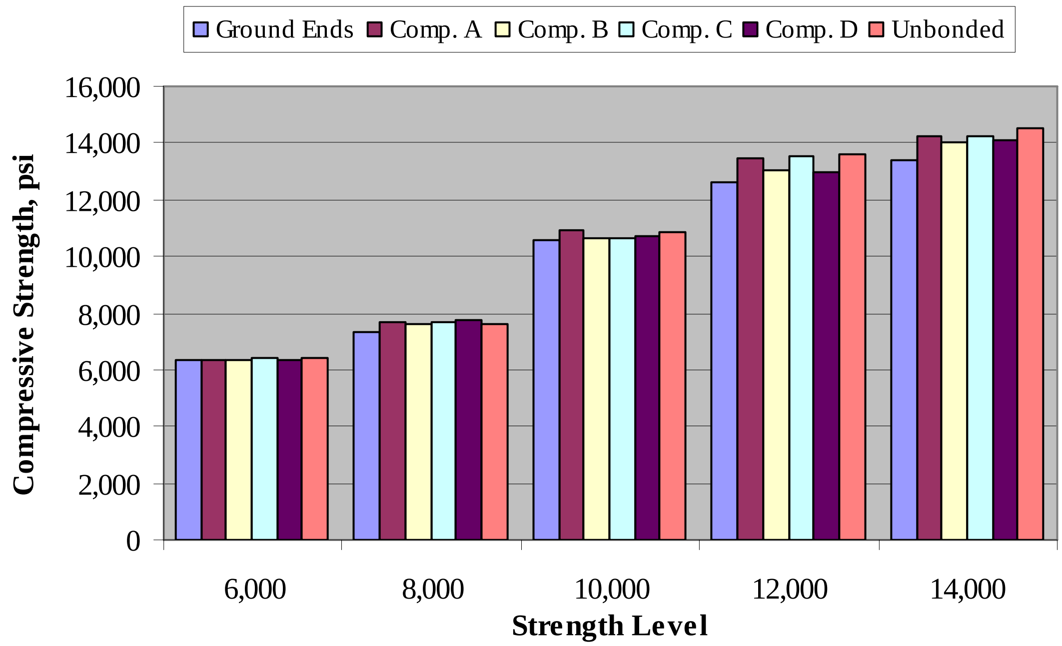


Figure 7
Mean compressive strength per strength level

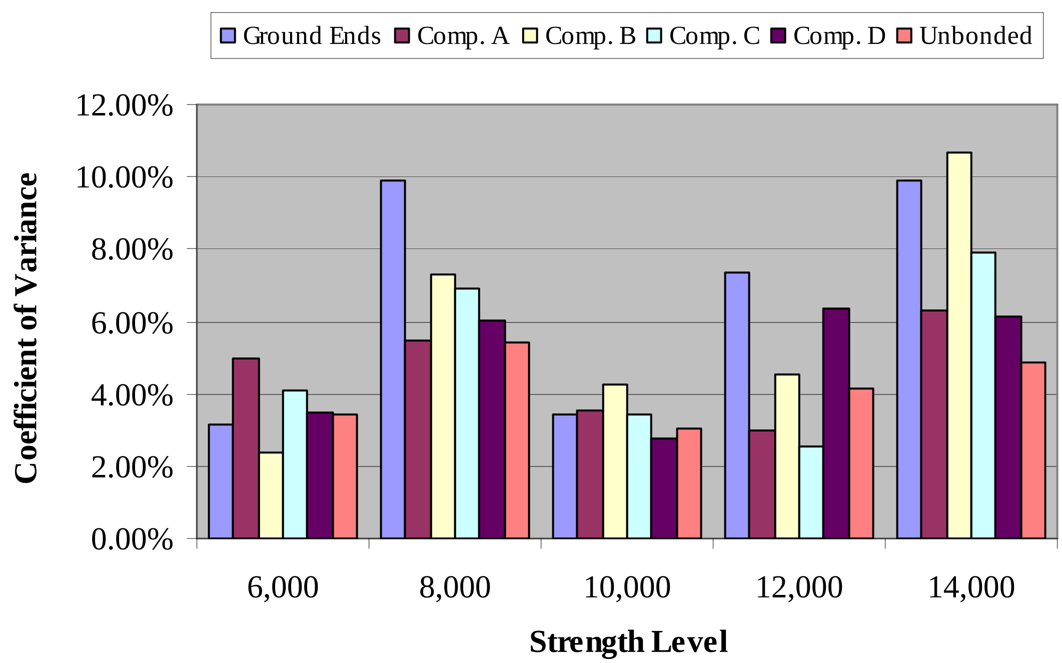


Figure 8
Comparison of coefficients of variance grouped by strength level

The highest coefficient of variance (10.7 percent) is produced by Capping B at the 14,000 psi strength level. This same compound produces the lowest coefficient of variance (2.4 percent) at the 6,000 psi strength level. Ground ends produced coefficients of variance of 9.9 percent at the 8,000 psi and 14,000 psi levels, and 7.4 percent at the 12,000 psi level. For the 6,000 psi and 10,000 psi strength levels, ground ends produced coefficients of variance of 3.1 percent and 3.4 percent, respectively. Capping compounds A and C followed a similar pattern of producing their lowest variations at the 10,000 and 12,000 psi levels, and the highest ones at the 6,000 psi, 8,000 psi, and 14,000 psi levels. Compound D shows a variability pattern similar to the unbonded pads with the highest variability at the 8,000 psi, 12,000 psi, and 14,000 psi levels, and the lowest variations at the 6,000 psi and 10,000 psi levels. These patterns are apparent when the coefficients of variance are grouped by end conditions as presented in Figure 9. The individual coefficients of variance for each capping system indicate that the variability of a particular capping system is not always the same at different strength levels. For example, the ground ends seem to have a low variation at the 6,000 psi and 10,000 psi levels, but they have a high variability at the other levels. The source of variation might be related to the material, such batch-to-batch variations. For this reason a comprehensive analysis that looks into the effects of the end conditions and also takes in to account the different batches is more useful at determining any differences due to the capping systems.

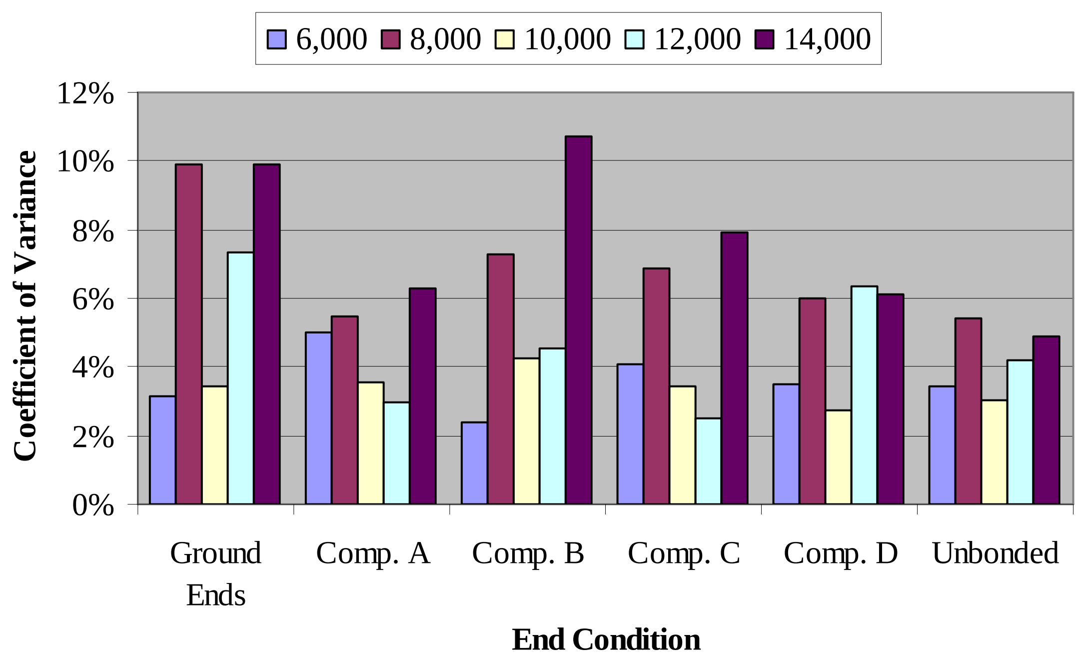


Figure 9
Comparison of coefficients of variance grouped by end condition

The overall variation for the 6,000 psi and 10,000 psi levels is acceptable and can be classified as very good, the variation for the 12,000 psi level is higher, but it can be classified as good. The variations for the 8,000 psi and 14,000 psi levels are classified as poor according to the standards of concrete control for compressive strength over 5,000 psi [9]. This indicates that the variability of some groups is not as small as desirable. Figure 10 presents a comparison of the variation values mentioned above. The values shown in Figure 10 were obtained by calculating the coefficients of variance for all the data in a particular strength level.

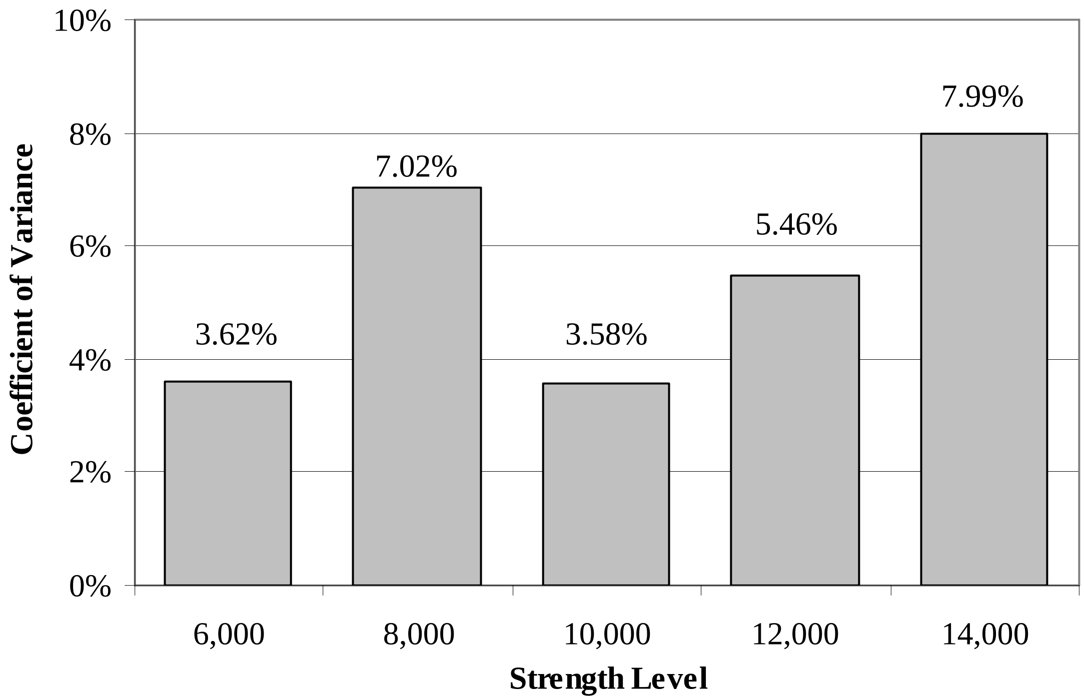


Figure 10
Coefficients of variance for compressive strength levels

The variability of the end conditions can be compared by normalizing the data by dividing each value by its corresponding mean compressive strength and then grouping the data by end condition regardless of strength level. The coefficients of variance for each end condition were calculated and are presented in a comparison in figure 11. The unbonded pads provided a coefficient of variance of 4.33 percent, which is the smallest of all the end treatments. The capping compounds provided values that ranged from 4.77 percent to 6.35 percent. The highest coefficient of variance was provided by the ground ends with 7.33

percent. This indicates that the ground ends provided an increase in variability of about 70 percent over the unbonded pads. As established by ACI *[27]*, the unbonded pads, with their small variability, were the only group to be classified as "very good". The capping compounds fall within the "good" and "fair" classifications, while the ground ends variability is so high that it is considered "poor".

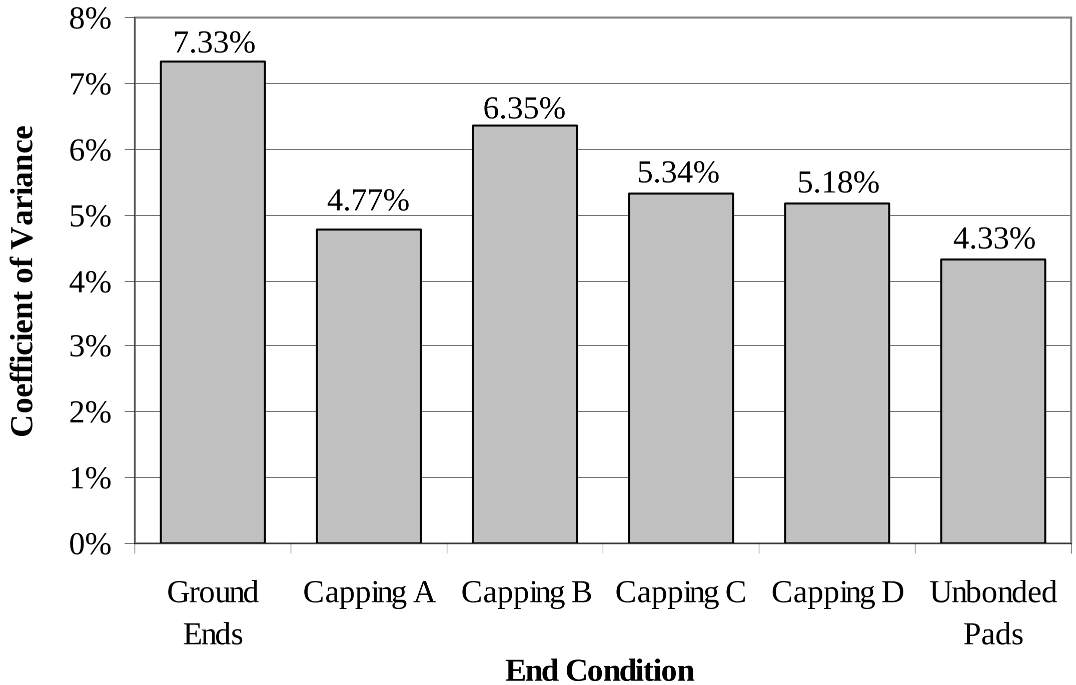


Figure 11
Coefficients of variance for end conditions

Taking the range of each group and normalizing it by dividing it by the group's mean compressive strength gives an idea of the spread of the data for an individual group and also allows for comparison between groups. This was done for the data in the investigation. A chart showing the values is presented in figure 12, which shows that the 6,000 psi and 10,000 psi groups have the lowest spread and the 14,000 psi group has the largest spread. A pattern can be observed from this information—the range of the data seems to increase as the mean compressive strength increases. The obvious large spread of the 8,000 psi group with a value similar to the 14,000 psi group can be explained by analyzing the data grouped by batch for each strength level. A large difference in mean compressive strength was observed between the batches at the 8,000 psi group. Analyzing the data of the 8,000 psi level by batches shows that two of the batches had a mean around 7,100 psi and the other three batches had a mean around 7,950 psi. This increased the overall spread of the data at this strength level.

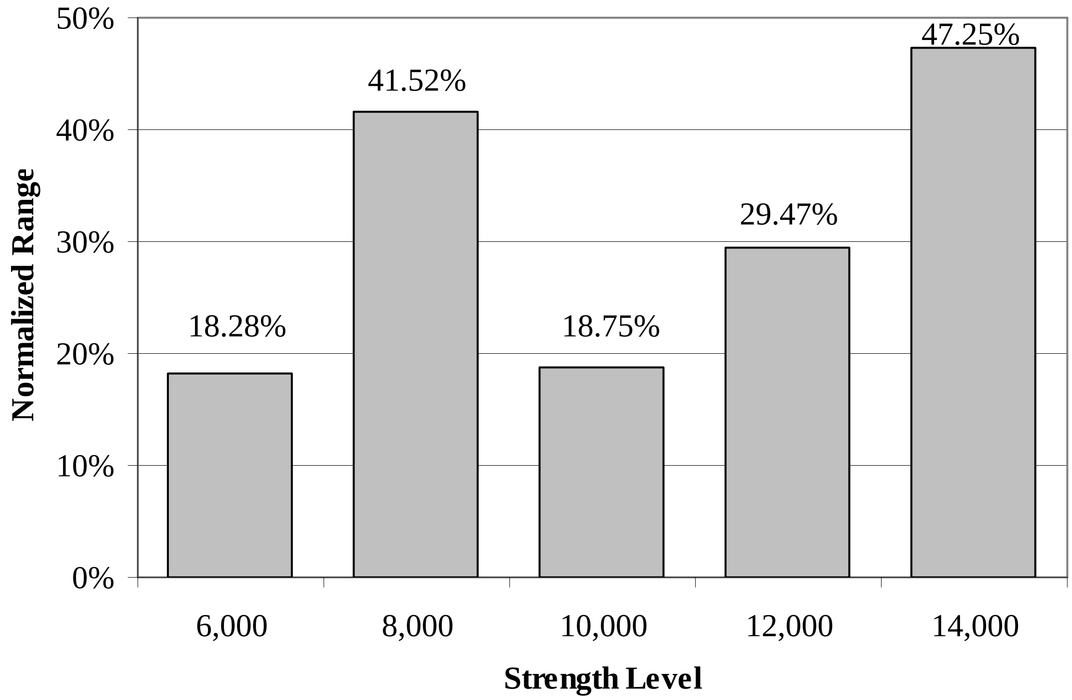


Figure 12
Range comparison by strength level

A trend can be observed when the bonded and unbonded systems are compared to the ground ends. As the strength level increases, the difference between the bonded and unbonded systems and the ground ends seems to increase. Figure 13 illustrates this trend, which is more apparent at the higher strength levels (12,000 and 14,000 psi).

Goodness of fit tests for compressive strength data

Chi-square tests were performed to verify the distribution of the test results. The data was compared to a normal distribution with an equal mean and standard deviation as the test data. The alpha value for these tests was set at 5 percent. The comparisons were made for all test results on a given strength level, and for each end condition within a strength level. Histograms showing the distribution of the data are shown in the Appendix.

When all the data grouped by strength levels are analyzed by a goodness of fit test, the results show that the data followed a normal distribution only at the 6,000 psi and 10,000 psi levels. Statistic values and the test results are shown in table 5. The results also showed that most of the data follows a normal distribution when the same analysis is performed for the individual end conditions for each strength level. The data that does not follow the normal distribution comes from Compound A at the 8,000 psi strength level, and Compounds B and C at the 14,000 psi strength level. The data for the 12,000 psi level follows a normal distribution when it is separated by end conditions. The test results for the individual end conditions are shown in table 6.

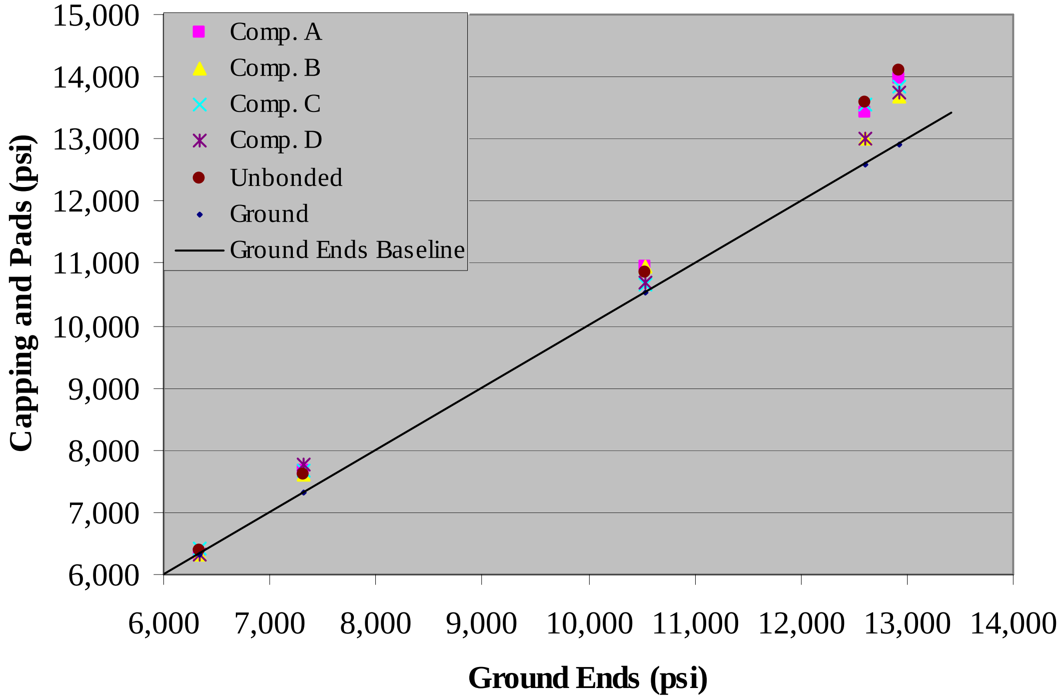


Figure 13
Relationship between compressive strengths from various end conditions

Table 5
Results of best-fit test for all data in a strength level

Strength Level	Statistic Value	Result
6,000	2.7748	Pass
8,000	76.305	Fail
10,000	1.7007	Pass
12,000	29.957	Fail
14,000	302.41	Fail

Note: The C-statistic is compared to C-critical of 9.4877, obtained from a Chi-Square distribution table for an alpha of 5 percent and 4 degrees of freedom.

Table 6
Results of best-fit test for data in an end condition

Strength Level	End Condition	Statistic Value	Result
6,000	Ground Ends	4.4380	Pass
	Compound A	2.4947	Pass
	Compound B	2.4996	Pass
	Compound C	0.0643	Pass
	Compound D	4.4476	Pass
	Unbonded Pads	4.2395	Pass
8,000	Ground Ends	2.4025	Pass
	Compound A	8.6365	Fail
	Compound B	1.3047	Pass
	Compound C	1.5127	Pass
	Compound D	2.4671	Pass
	Unbonded Pads	3.3051	Pass
10,000	Ground Ends	0.3819	Pass
	Compound A	0.4048	Pass
	Compound B	0.1066	Pass
	Compound C	0.4345	Pass
	Compound D	3.9441	Pass
	Unbonded Pads	2.2667	Pass
12,000	Ground Ends	0.6567	Pass
	Compound A	0.7980	Pass
	Compound B	3.8826	Pass
	Compound C	2.0836	Pass
	Compound D	4.7325	Pass
	Unbonded Pads	1.3961	Pass
14,000	Ground Ends	2.2329	Pass
	Compound A	1.7179	Pass
	Compound B	26.394	Fail
	Compound C	8.0736	Fail
	Compound D	1.2695	Pass
	Unbonded Pads	2.5626	Pass

Note: The C-statistic is compared to C-critical of 5.9915, obtained from a Chi-Square distribution table for an alpha of 5 percent and 2 degrees of freedom.

Differences between end conditions for strength levels

As mentioned before, the test cylinders for this investigation were obtained from various batches and then they were assigned an end condition. Basically, the sample of experimental units was divided into groups (batches) and the treatments (end conditions) were assigned randomly to the units (cylinders) in each group. This experiment is therefore considered a randomized block design (RBD). The data resulting from this arrangement have two sources of variation. In this case the variation is due to the batches and to the end conditions. The advantage of this design is that it allows the known sources of variation to be kept out of the error term of the ANOVA *[29]*.

The data was analyzed using a statistical software package to detect any differences in compressive strengths between the end conditions *[30]*. An ANOVA test was performed for each strength level to detect any differences between the means of the end conditions. Then, if a difference was detected, a Tukey post-ANOVA procedure was used to determine which means were significantly different from each other. A confidence level of 95 percent was used for these tests. This procedure was selected because it is a conservative method that provides a higher level of protection against incorrectly rejecting the null hypothesis when it is true (Type I error). The results from the analysis are discussed below.

A summary of the ANOVA results is shown in table 7. This table presents the F-values calculated by the statistical software. The values calculated are then compared to the critical values for rejection or acceptance of the hypothesis of equal means. If the F-value is greater than the critical F-value the means are not equal. The critical values calculated for a 95 percent confidence level are also shown in table 7. The analysis detected differences of the batches at all strength levels except at the 12,000 psi level, reinforcing the use of the RBD experiment. The ANOVA for the 6,000 psi group confirms that the end conditions do not seem to have an effect at this strength level; the same can be concluded for the 10,000 psi group. The ANOVA does not detect any significant differences at the 14,000 psi level due to its high variability. However, at the 8,000 psi and 12,000 psi strength levels, significant differences are detected in the compressive strength due to the end conditions.

The results for the Tukey post-ANOVA test are shown in table 8 for the 8,000 psi level and table 9 for the 12,000 psi level. These tables present the end conditions with their respective mean compressive strength and grouping. The grouping letters, which are assigned by the statistical software, signify that the compressive strength means that have the same letter are not significantly different. From the post-ANOVA test performed for the 8,000 psi group, it can be concluded that the ground ends have significantly lower compressive strengths than the capping compounds A, C, and D. The post-ANOVA test for the 12,000 psi group leads to the conclusion that the compressive strength from ground ends is significantly lower than Capping C and unbonded pads. No other clear statistical distinction can be made from the analysis. It is interesting to note that, although the ground ends produced lower compressive strength at all levels but the 6,000 psi level, only in the 8,000 psi and 12,000 psi groups was a difference detected between the ground ends and the rest of the capping systems. This behavior can be explained by the high variability of the ground ends system. No significant difference is detected between the end treatments when the ground ends are removed from the data set.

Table 7
Summary of ANOVA results for differences between end conditions and batches

Strength Level	F Values	
	Batch	End Condition
6,000	15.39	0.71
8,000	41.29	3.93
10,000	2.91	1.76
12,000	1.80	4.28
14,000	11.72	2.18
Critical F Values (95% confidence level)	2.86	2.71

Table 8
Tukey grouping for 8,000 psi group (minimum significant difference = 354 psi)

Grouping		End Condition	Mean Compressive Strength
	A	Capping D	7,772
	A	Capping A	7,687
	A	Capping C	7,676
B	A	Unbonded Pads	7,608
B	A	Capping B	7,603
B		Ground Ends	7,313

Table 9
Tukey grouping for 12,000 psi group (minimum significant difference = 840 psi)

Grouping		End Condition	Mean Compressive Strength
	A	Unbonded Pads	13,599
	A	Capping No. C	13,548
B	A	Capping No. A	13,435
B	A	Capping No. B	13,023
B	A	Capping No. D	13,000
B		Ground Ends	12,601

Capping Compound Thickness

The thickness of the bonded caps was measured for the cylinders in the 14,000 psi group. Three measurements were taken from both caps of each cylinder after being tested. The measurements ranged from 0.049 to 0.196 in. and had a mean value of 0.107 in. These measurements are within the specified capping thicknesses for concrete with compressive strengths greater than 7,000 psi as required by ASTM C 617 *[7]*. The data has a high coefficient of variance at 29.7 percent. Table 10 presents the mean thickness of the bonded caps. The individual measurements are presented in the Appendix.

The data was grouped together and a Chi-Squared analysis was performed to determine the distribution that best fits the collected data. It was determined that the measured thickness of the bonded caps followed a lognormal distribution at the 95 percent confidence level. No specific pattern was observed as of the thinner capping giving better results than thicker capping or vice versa.

Table 10
Average thickness measured for bonded caps (in.)

Batch No.	Compound A	Compound B	Compound C	Compound D
21	0.130	0.113	0.091	0.115
22	0.116	0.109	0.088	0.097
23	0.104	0.094	0.097	0.098
24	0.094	0.097	0.124	0.070
25	0.121	0.144	0.097	0.137

CONCLUSIONS

This investigation focused on evaluating commonly used capping systems for testing the compressive strength of high-strength concrete cylinders. Six capping systems were evaluated at five strength levels that ranged from 6,000 to 14,000 psi. The findings of this study will help testing laboratories determine which system will provide consistent results for compressive strength of high-strength concrete. The conclusions of this investigation are as follows:

- The variability of compressive strength between capping systems tends to increase as the strength level increases.
- The ground ends have the highest variability of the systems investigated.
- The ground ends seem to have a much higher variance compared to the unbonded pads at higher strength levels.
- The unbonded pads have the lowest variability of the systems investigated.
- The ground ends produced lower strength results for all strength levels above 6,000 psi.
- The ground ends produced significantly different lower strengths at the 8,000 psi and 12,000 psi levels.
- Unbonded pads produced compressive strengths that were either higher than all other systems or not different from compressive strengths produced by the bonded caps.
- Thinner capping caps did not seem to produce higher compressive strengths than the thick capping caps.
- Implications from this study indicate no significant statistical differences or advantages of one capping system over another to test compressive strength of high-strength concrete.

RECOMMENDATIONS

The end conditions investigated in this study provided similar results for the different strength levels. The use of unbonded pads for testing compressive strength of HSC seems reasonable, based on the data collected and on the lower variability obtained when compared to the other methods. The researchers also recommend including the unbonded neoprene pads in the LADOTD test procedures as an advised alternative for testing high-strength concrete cylinders used for acceptance. Another benefit of this method is that it requires the least amount of preparation time of the methods studied here.

As recommendations for future investigation, investigators can consider concentrating on one of the strength levels (10,000 or 12,000 psi) and increase the sample population for the study. In this investigation, the planeness and perpendicularity were checked for compliance with the test methods; it is recommended that in a future investigation, this data is measured and recorded. The data collected will provide more information for determining the effects that these properties can have in the compressive strength result using various capping systems. Researchers also recommend including the use of unbonded pads with Shore A Durometer hardness higher than 70 to determine if it has an effect on the compressive strength result.

REFERENCES

1. Richardson, D. N. "Effects of Testing Variables on the Comparison of Neoprene Pad and Sulfur Mortar-Capped Concrete Test Cylinders." *ACI Materials Journal*, Vol 87, No. 5, September 1990, pp. 489-485.

2. ACI Committee 363, "Guide to Quality Control and Testing of High-Strength Concrete," ACI 363.2R-98, American Concrete Institute, 1998, p. 18.

3. ACI Committee 363, "State-of-the-Art Report on High-Strength Concrete," ACI 363R-92, American Concrete Institute, 1992, p. 55.

4. Kosmatka, S.H., Kerkhoff, B., and Panarese, W.C., *Design and Control of Concrete Mixtures*, 14th edition, Portland Cement Association, Skokie, Illinois, 2002, 358 pages.

5. Ali, F.A., Abu,-Tair, A., O'Connor, D., Benmarce, A., and Nadjai, A. "Useful and Practical Hints on the Process of Producing High-Strength Concrete." *Practice Periodical on Structural Design and Construction*, Vol. 6, No. 4, November 2001, pp. 150-153.

6. Rosenbaum, D.B. "Is Concrete Becoming Too Strong to Test?" *Engineering News Record*, Vol. 224, No. 3, January 1990, pp. 56-58.

7. 2004 Annual Book of ASTM Standards, ASTM C 617-98, "Standard Practice for Capping Cylindrical Concrete Specimens," Vol. 04.02, American Society for Testing and Materials, Philadelphia, 2004.

8. 2004 Annual Book of ASTM Standards, ASTM C 1231-00, "Standard Practice for Use of Unbonded Caps in Determination of Compressive Strength of Hardened Concrete Cylinders," Vol. 04.02, American Society for Testing and Materials, Philadelphia, 2004.

9. Gonnerman, H. F., "Effect of End Condition of Cylinder in Compression Tests of Concrete," *ASTM Proceedings*, Vol. 24, Part II, 1924, pp. 1036-1065.

10. Purrington, W. F. and Mc Cormick, J., "A Simple Device to Obviate Capping of Concrete Specimens," *ASTM Proceedings*, Vol. 26, Part II, 1926, pp. 488-492.

11. Freeman, P. J., "Capping Device for Concrete Cylinders," *Engineering News Record*, Vol. 101, November 1928, p. 777.

12. Freeman, P. J., “Method of Capping Concrete Cylinders using Sulfur Compound,” *ASTM Proceedings,* Vol. 30, 1930, pp. 518-520.

13. Timms, A. G., “Sulfur for Capping Test Cylinders?” *ACI Journal*, Vol. 10, No. 5, April 1939, pp. 420-421.

14. Troxell, G.E. “The Effects of Capping Methods and End Condition Before Capping Upon the Compressive Strength of Concrete Test Cylinders.” *Proceedings of the Annual Meeting, American Society for Testing Materials*, Vol. 41, 1942, pp. 1038-1045.

15. Kennedy, T.B., “A Limited Investigation of Capping Materials for Concrete Test Specimens,” *Journal of the American Concrete Institute*, Vol. 16, No. 2, November 1944, pp. 117-126.

16. Werner, G., “The Effect of Capping Material on the Compressive Strength of Concrete Cylinders,” *ASTM Proceedings,* Vol. 58, 1958, pp. 1166-1186.

17. Grygiel , J. S. and Amsler, D.E. *Capping Concrete Cylinders with Neoprene Pads.* Research Report 46, Engineering Research and Development Bureau, New York State Department of Transportation, State Campus, Albany, NY, April 1977.

18. Carrasquillo, P.M., and Carrasquillo, R.L., “Effect of Using Unbonded Capping Systems on the Compressive Strength of Concrete Cylinders,” *ACI Materials Journal*, Vol. 85, No. 3, May 1988, pp. 141-147.

19. Lessard, M., Chaallal, O., and Aïtcin, P-C "Testing High-Strength Concrete Compressive Strength", *ACI Materials Journal*, Vol 90, No. 4, July 1993, pp. 303-307.

20. Pistilli, M. F. and Willems, T. “Evaluation of Cylinder Size and Capping Method in Compression Strength Testing of Concrete.” *Cement, Concrete, and Aggregates,* CCAGDP, Vol. 15, No. 1, 1993, pp. 59-69.

21. Boulay, C., and De Larrard, F. “The Sand-Box.” *Concrete International*, Vol. 15, No. 4, April 1993, pp. 63-66.

22. French, C. W. and Mokhtarzadeh, A., “High-Strength Concrete: Effects of Materials, Curing and Test Procedures on Short-Term Compressive Strength,” *PCI Journal*, Vol. 38, No. 3, May/June 1993, pp. 76-87.

23. Carino, N. J., Guthrie, W. F., Lagergren, E. S., and Mullings, G. M., “Effects of Testing Variables on the Strength of High-Strength (90 MPa) Concrete Cylinders,”

High-Performance Concrete Special Publication No. SP-149, American Concrete Institute, Farmington Hills, MI, 1994, pp. 589-632.

24. Lobo, C L., Mullings, G. M., and Gaynor, R. D. “Effect of Capping Materials and Procedures on the Measured Compressive Strength of High-Strength Concrete.” *Cement, Concrete, and Aggregates*, CCAGPD, Vol. 16, No. 2, Dec. 1994, pp. 173-180.

25. Vichit-Vadakan, W., Carino, N. J., and Mullings, G. M. “Effect of Elastic Modulus of Capping Material on Measured Strength of High-Strength Concrete Cylinders,” *Cement, Concrete, and Aggregates*, CCAGDP, Vol. 20, No. 2, December 1998, pp. 227-234.

26. Burg, R.G, Caldarone, M.A., Detwiler, G., Jansen, D.C., and Willems, T.J. “Compression Testing of SC: Latest Technology.” *Concrete International*, Vol. 21, No. 8, August 1999, pp. 67-76.

27. ACI Committee 214, “Evaluation of Strength Test Results of Concrete,” ACI 214R-02, American Concrete Institute, 2002, p. 20.

28. Mullarky, J. I., and Wathne, L. “Capping Cylinders for Testing High Strength Concrete,” *HPC Bridge Views*, No. 14, March 2001, pp. 3.

29. Freund, R. J., and Wilson, W. J., *Statistical Methods*, Academic Press, San Diego, 1997.

30. SAS Institute Inc., *SAS/STAT 9.1 User’s Guide*. SAS Institute Inc., Cary, NC, 2004.

APPENDIX

The following tables present the individual test results obtained for analysis in this investigation. Table 11 presents the results from the compressive strength tests performed on the capping compounds.

Tables 12 thru 16 present the compressive strength results for the cylinders tested. Each table presents the results for one strength level.

Table 17 presents the measurements from the caps used in the 14,000 psi level. Three readings were taken for each cap, and both caps were measured for each cylinder.

Table 11
Capping compound compressive strength results of 2 in. cubes (psi)

Compound A	Compound B	Compound C	Compound D
7,805	11,066	9,191	9,075
7,684	10,855	9,174	9,551
8,403	10,244	9,181	9,613
9,863	10,502	9,906	7,873
10,144	11,030	9,689	7,633
9,896	10,800	11,455	8,199
9,800	10,264	9,439	8,684
9,762	11,028	11,151	8,202
10,146	11,078	10,407	8,234

Table 12
Compressive strength data for 6,000 psi strength level

End Condition	Batch No. 1	Batch No. 2	Batch No. 3	Batch No. 4	Batch No. 5
Ground Ends	6,190	6,290	6,090	6,860	6,490
	6,130	6,170	6,290	6,410	6,360
	6,340	6,140	6,420	6,540	6,270
Capping Compound A	6,230	5,880	6,080	6,770	6,350
	6,210	6,160	6,520	6,970	6,500
	5,940	6,030	6,110	6,680	6,280
Capping Compound B	6,350	6,190	6,340	6,190	6,460
	6,090	6,280	6,320	6,570	6,400
	6,380	6,340	6,060	6,280	6,560
Capping Compound C	6,430	6,270	6,280	6,740	6,630
	6,210	6,200	6,380	6,830	6,510
	6,280	5,920	6,110	6,700	6,680
Capping Compound D	6,360	6,140	6,370	6,300	6,330
	5,860	6,320	6,460	6,730	6,430
	6,390	5,930	6,250	6,340	6,580
Unbonded Pads	6,610	6,360	6,170	6,650	6,480
	6,300	6,190	6,510	6,600	6,380
	5,810	6,280	6,470	6,560	6,400

Table 13
Compressive strength data for 8,000 psi strength level

End Condition	Batch No. 6	Batch No. 7	Batch No. 8	Batch No. 9	Batch No. 10
Ground Ends	6,880	7,660	7,860	7,750	6,890
	7,040	8,080	8,100	7,700	5,440
	6,420	7,620	7,290	7,970	7,000
Capping Compound A	6,860	8,200	7,780	7,940	7,340
	7,340	7,940	8,020	8,000	7,250
	7,290	8,270	7,900	7,910	7,270
Capping Compound B	6,870	7,940	7,780	8,100	7,470
	7,460	8,420	8,200	8,100	7,110
	6,980	6,580	8,100	7,700	7,240
Capping Compound C	7,070	7,970	8,140	8,130	7,160
	7,240	7,950	8,170	7,790	7,280
	6,490	8,280	8,130	7,930	7,410
Capping Compound D	7,230	8,600	7,930	8,030	7,310
	7,070	8,200	8,080	7,950	7,310
	7,190	8,210	8,110	7,900	7,460
Unbonded Pads	7,010	8,370	7,860	8,130	7,240
	7,130	7,880	7,410	8,040	7,120
	7,420	7,650	7,630	7,900	7,330

Table 14
Compressive strength data for 10,000 psi strength level

End Condition	Batch No. 11	Batch No. 12	Batch No. 13	Batch No. 14	Batch No. 15
Ground Ends	10,720	10,480	10,520	11,030	10,450
	11,060	10,860	10,380	10,620	10,200
	10,060	10,700	9,790	10,340	10,960
Capping Compound A	11,160	11,100	10,590	11,200	10,870
	10,720	11,410	10,500	11,270	10,970
	11,090	10,860	10,420	11,780	10,400
Capping Compound B	10,440	11,030	10,550	11,070	10,750
	10,080	10,730	10,410	10,760	11,580
	9,770	10,580	10,140	11,080	10,810
Capping Compound C	10,850	10,460	10,770	11,180	10,530
	10,620	10,230	10,420	11,060	10,180
	10,890	10,680	10,010	11,270	10,640
Capping Compound D	10,630	10,630	10,780	11,310	11,010
	10,390	10,480	10,380	10,580	10,600
	11,100	10,410	10,940	10,650	10,310
Unbonded Pads	10,690	11,000	10,690	11,200	10,980
	10,340	10,390	11,150	10,440	11,300
	10,610	10,990	10,700	10,750	11,370

Table 15
Compressive strength data for 12,000 psi strength level

End Condition	Batch No. 16	Batch No. 17	Batch No. 18	Batch No. 19	Batch No. 20
Ground Ends	13,320	14,220	12,700	12,960	12,840
	13,810	13,000	12,000	11,660	10,800
	13,520	11,610	12,470	12,330	11,780
Capping Compound A	13,690	13,610	13,660	12,930	13,090
	13,970	13,080	12,950	13,330	13,610
	13,870	14,100	13,550	12,890	13,190
Capping Compound B	13,360	13,740	13,540	13,320	13,650
	11,810	11,960	13,160	13,260	12,900
	13,440	12,790	12,980	13,140	12,290
Capping Compound C	12,930	13,740	13,300	13,160	13,710
	13,710	14,290	13,320	13,360	13,520
	13,730	14,050	13,440	13,550	13,410
Capping Compound D	13,580	13,470	13,600	13,290	12,730
	12,040	13,380	12,490	12,790	13,490
	10,960	14,110	12,040	13,640	13,390
Unbonded Pads	14,140	14,080	13,820	12,900	13,400
	13,630	14,690	13,970	13,260	13,220
	13,670	14,280	12,680	13,250	12,990

Table 16
Compressive strength data for 14,000 psi strength level

End Condition	Batch No. 21	Batch No. 22	Batch No. 23	Batch No. 24	Batch No. 25
Ground Ends	12,300	12,230	14,710	14,360	13,410
	10,610	13,990	15,030	14,590	13,230
	11,710	12,070	14,250	14,360	14,360
Capping Compound A	13,340	13,040	15,300	14,860	15,100
	13,430	14,150	14,980	14,480	13,770
	13,520	12,830	15,730	14,300	14,990
Capping Compound B	13,860	13,410	15,250	14,870	14,660
	13,490	13,690	9,080	14,910	14,840
	14,010	13,840	14,290	15,230	14,800
Capping Compound C	12,560	13,400	15,500	15,300	14,260
	13,140	12,860	13,250	15,400	15,440
	13,440	13,390	15,400	15,380	15,030
Capping Compound D	12,650	13,380	14,140	14,710	14,700
	12,900	13,490	15,430	15,000	14,550
	13,190	14,120	14,810	13,740	15,150
Unbonded Pads	14,200	14,100	15,410	15,740	14,290
	13,480	13,610	14,830	15,020	15,350
	13,740	13,830	14,290	14,810	14,970

Table 17
Thicknesses measured for bonded caps (in.)

Batch No.	Compound A		Compound B		Compound C		Compound D	
	Cap No. 1	Cap No. 2	Cap No. 1	Cap No. 2	Cap No. 1	Cap No. 2	Cap No. 1	Cap No. 2
21	0.196	0.090	0.125	0.100	0.075	0.126	0.138	0.108
	0.146	0.075	0.130	0.090	0.075	0.117	0.073	0.132
	0.100	0.175	0.115	0.120	0.075	0.075	0.092	0.146
22	0.080	0.108	0.106	0.119	0.068	0.089	0.072	0.113
	0.134	0.174	0.097	0.138	0.077	0.107	0.072	0.152
	0.096	0.105	0.086	0.108	0.092	0.093	0.099	0.071
23	0.080	0.125	0.115	0.135	0.140	0.150	0.095	0.102
	0.083	0.120	0.089	0.098	0.076	0.079	0.136	0.135
	0.125	0.090	0.063	0.061	0.063	0.072	0.061	0.059
24	0.103	0.098	0.111	0.077	0.135	0.133	0.064	0.057
	0.082	0.082	0.081	0.104	0.145	0.084	0.066	0.090
	0.103	0.096	0.150	0.056	0.146	0.101	0.049	0.092
25	0.095	0.111	0.165	0.115	0.087	0.101	0.080	0.073
	0.110	0.144	0.145	0.130	0.073	0.085	0.175	0.154
	0.150	0.115	0.167	0.143	0.115	0.118	0.166	0.171

Histograms and Best Fit Data

The tables and figures presented in this section were used in the goodness of fit tests (Chi-Square tests). The intervals for the histograms were calculated with the following formula

$$K = 1 + 3.33 \cdot \log n$$

Where n is the number of observations in each case

The interval widths were calculated as:

$$w = \frac{range}{K - 1}$$

The initial interval limit was calculated as:

$$l_0 = \min - \frac{w}{2}$$

The rest of the interval limits were calculated by adding the interval width to the previous interval limit. The histograms were determined with a built-in function of the Mathcad software.

The theoretical frequencies were calculated based on a normal distribution with the same mean and standard deviation as the data being analyzed. Built-in functions of the Mathcad software were used to determine the cumulative probabilities between two consecutive interval limits. Then, these were multiplied by the number of observations to get the expected frequency for each interval.

A Chi-Squared test was performed to compare between the observed compressive strengths and the expected values for normally distributed data. This test compares two C-statistic values, one from the observed data and one from the normally distributed data. If the C-value calculated from the data is smaller than the C-critical value then it can be assumed than the data follows a normal distribution.

The C-value for the observed data was calculated with the following formula

$$\sum_{i=1}^{m} \frac{(n_i - e_i)^2}{e_i}$$

Where: n_i is the frequency at interval i

e_i is the theoretical frequency at interval i

m is the number of intervals

Then the C-critical value was calculated using the Mathcad functions for the Chi-Squared inverse cumulative probability distribution. This was done for a 95 percent confidence level, with 4 and 2 degrees of freedom for all the data and individual capping systems respectively. Tables 53 thru 57 present the comparison results.

Table 18
Histogram data for all end conditions at 6,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
5,713	5,810	3	2.474
5,906	6,003	8	10.186
6,100	6,196	27	23.959
6,293	6,390	29	28.882
6,486	6,583	14	17.855
6,680	6,776	8	5.652
6,873	6,970	1	0.992
7,066			
	Sum =	**90**	**90.000**

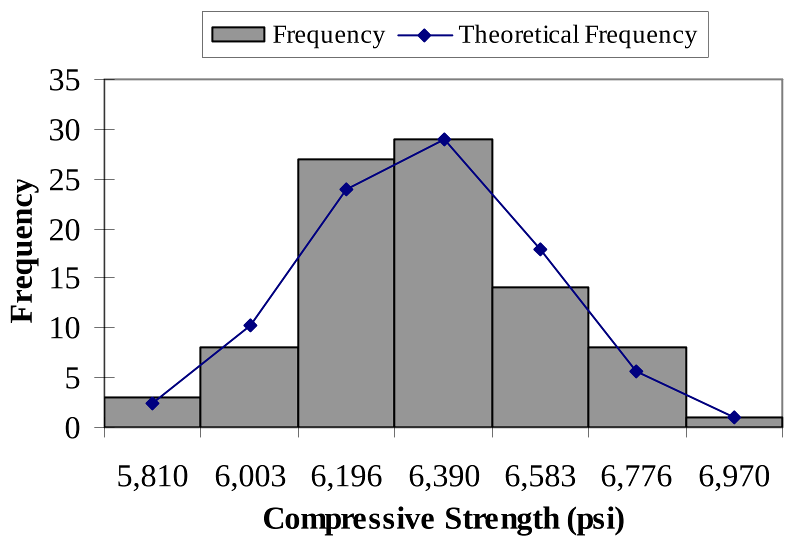


Figure 14
Histogram of all end conditions at the 6,000 psi level

Table 19
Histogram data for ground ends at 6,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
5,996	6,092	4	3.508
6,189	6,285	6	5.435
6,381	6,477	4	4.369
6,574	6,670	0	1.470
6,766	6,862	1	0.218
6,959			
	Sum =	**15**	**15.000**

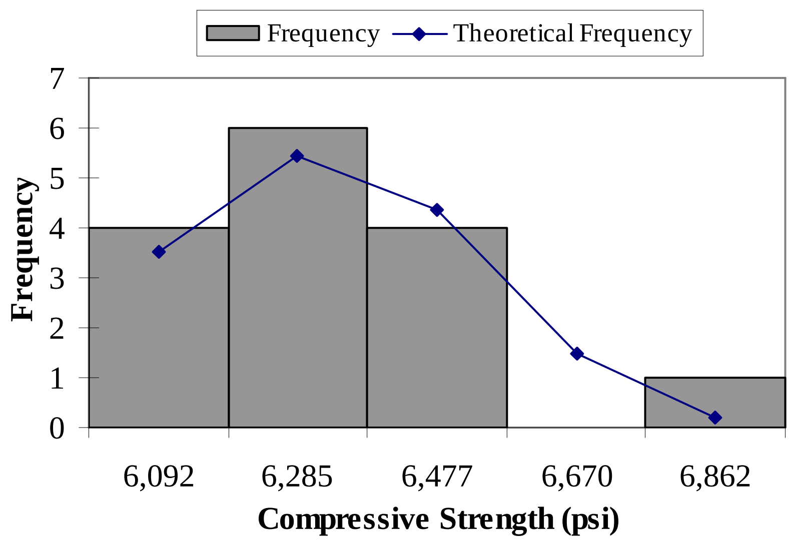


Figure 15
Histogram of ground ends data at the 6,000 psi level

Table 20
Histogram data for Compound A at 6,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
5,738	5,874	2	2.527
6,011	6,147	7	4.387
6,283	6,419	3	4.75
6,556	6,692	2	2.557
6,828	6,964	1	0.779
7,101			
	Sum =	**15**	**15.000**

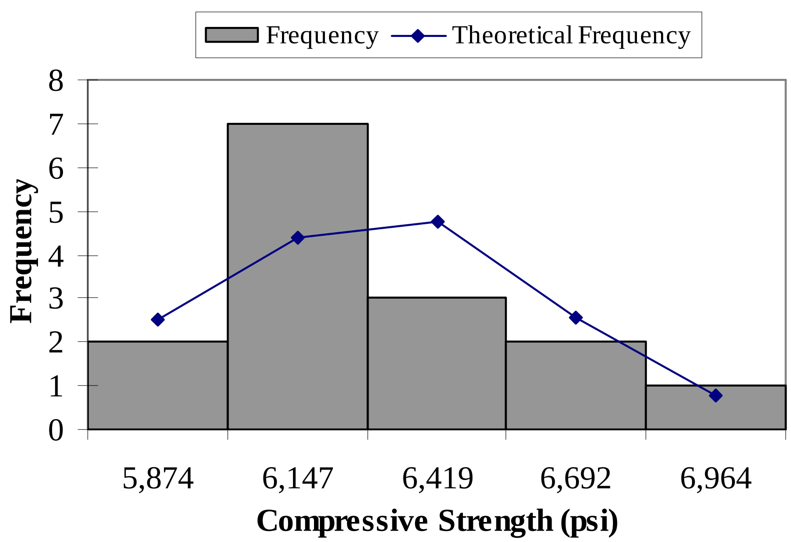


Figure 16
Histogram of Compound A data at the 6,000 psi level

Table 21
Histogram data for Compound B at 6,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
5,999	6,063	2	1.434
6,127	6,190	2	3.468
6,254	6,318	7	4.982
6,382	6,445	2	3.58
6,509	6,573	2	1.536
6,637			
	Sum =	**15**	**15.000**

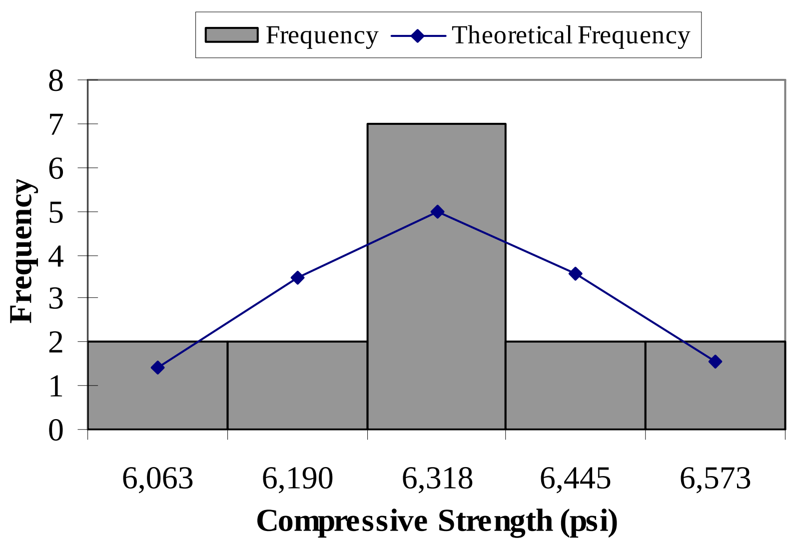


Figure 17
Histogram of Compound B data at the 6,000 psi level

Table 22
Histogram data for Compound C at 6,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
5,811	5,925	1	1.174
6,039	6,152	3	3.182
6,266	6,380	5	4.983
6,494	6,607	4	3.867
6,721	6,835	2	1.795
6,949			
	Sum =	**15**	**15.000**

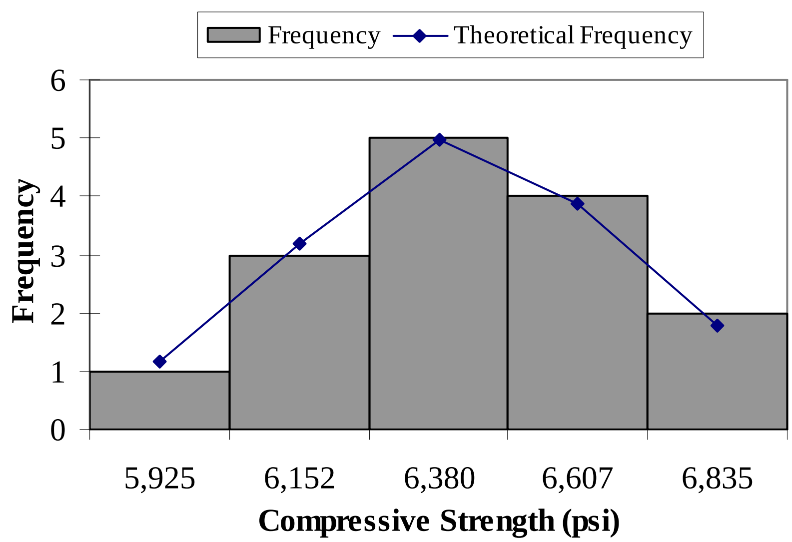


Figure 18
Histogram of Compound C data at the 6,000 psi level

Table 23
Histogram data for Compound D at 6,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
5,752	5,861	2	0.84
5,970	6,078	1	3.268
6,187	6,296	8	5.651
6,405	6,513	3	3.973
6,622	6,731	1	1.268
6,840			
	Sum =	**15**	**15.000**

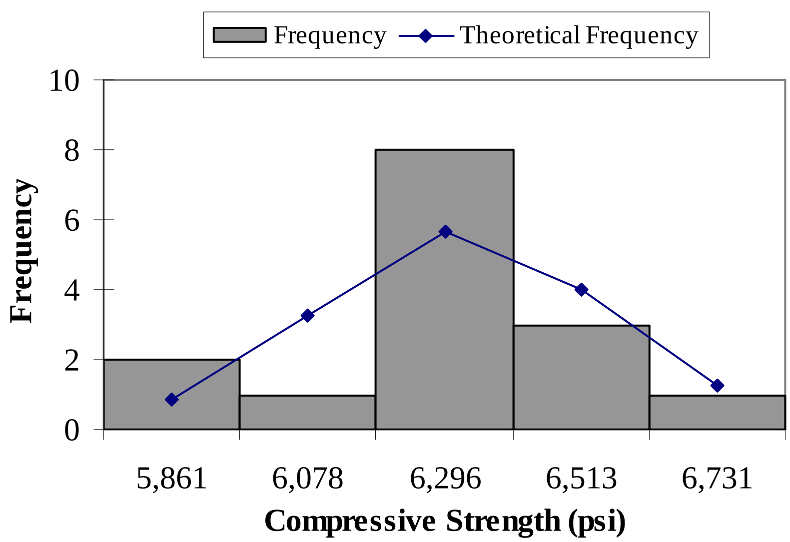


Figure 19
Histogram of Compound D data at the 6,000 psi level

Table 24
Histogram data for unbonded pads at 6,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
5,705	5,810	1	0.232
5,915	6,020	0	1.515
6,125	6,230	4	4.399
6,335	6,440	6	5.392
6,545	6,650	4	3.461
6,755			
	Sum =	**15**	**15.000**

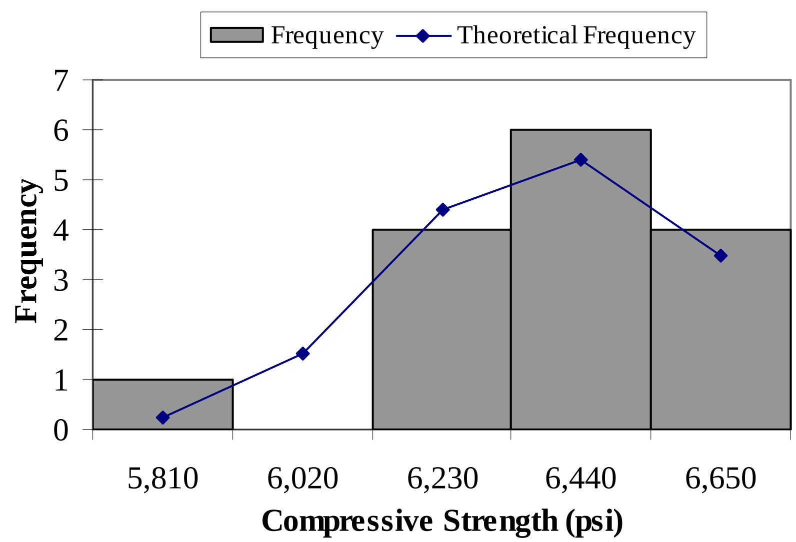


Figure 20
Histogram of unbonded pads data at the 6,000 psi level

Table 25
Histogram data for all end conditions at 8,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
5,177	5,440	1	0.016
5,703	5,967	0	0.423
6,230	6,493	3	4.511
6,757	7,020	22	19.380
7,283	7,547	23	33.812
7,810	8,073	38	24.050
8,337	8,600	3	7.808
8,863			
	Sum =	**90**	**90.000**

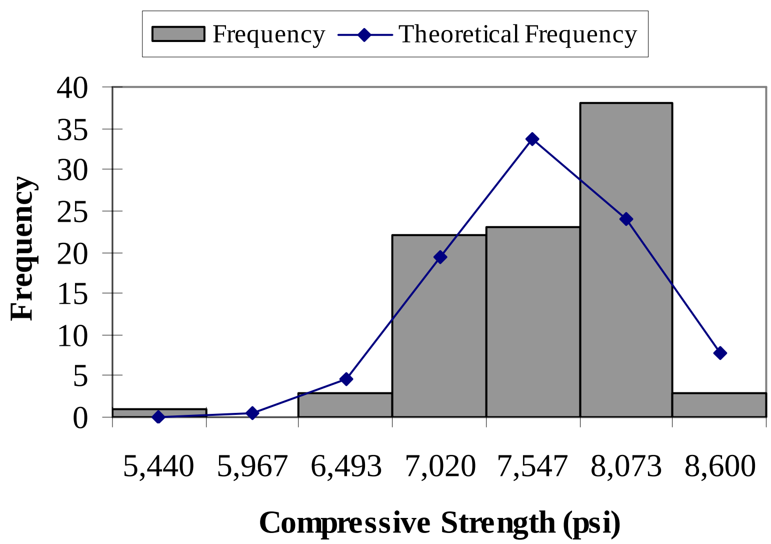


Figure 21
Histogram of all data at the 8,000 psi level

Table 26
Histogram data for ground ends at 8,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
5,108	5,440	1	0.250
5,773	6,105	1	1.448
6,438	6,770	4	4.084
7,103	7,435	5	5.240
7,768	8,100	4	3.979
8,433			
	Sum =	**15**	**15.000**

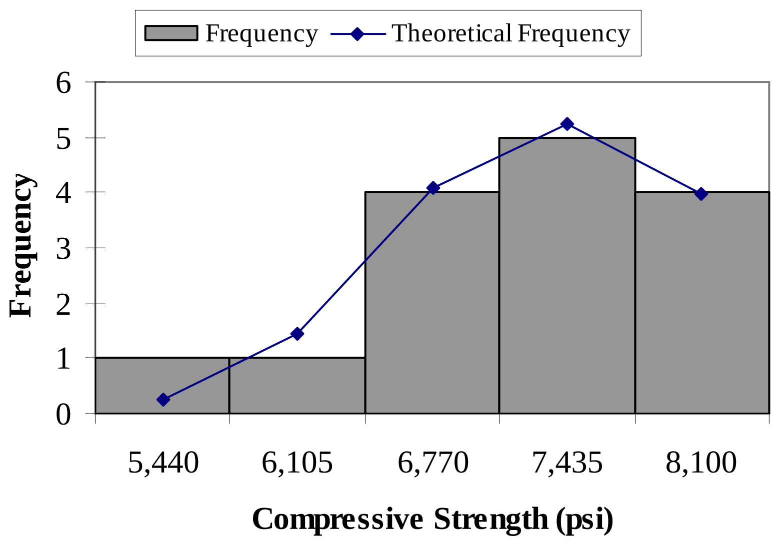


Figure 22
Histogram of ground ends data at the 8,000 psi level

Table 27
Histogram data for Compound A at 8,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
6,684	6,860	1	0.920
7,036	7,213	5	2.672
7,389	7,565	0	4.670
7,741	7,918	7	4.222
8,094	8,270	2	2.515
8,446			
	Sum =	**15**	**15.000**

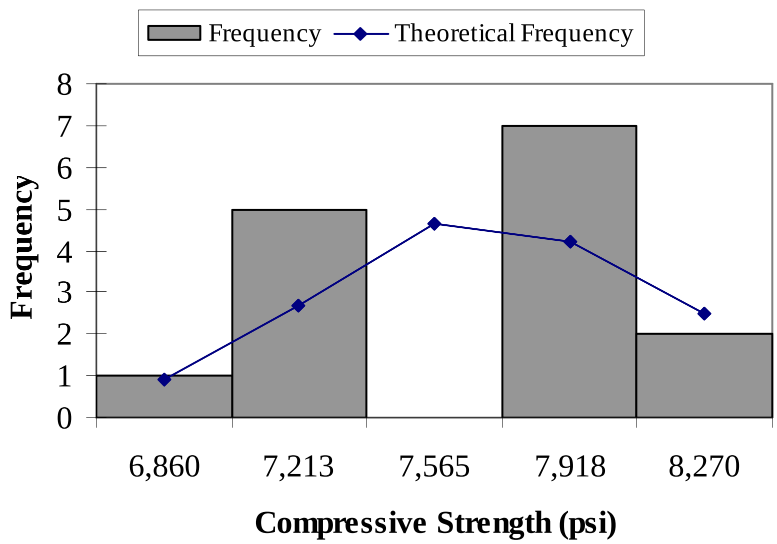


Figure 23
Histogram of Compound A data at the 8,000 psi level

Table 28
Histogram data for Compound B at 8,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
6,350	6,580	1	1.144
6,810	7,040	4	2.964
7,270	7,500	3	4.747
7,730	7,960	5	3.970
8,190	8,420	2	2.175
8,650			
	Sum =	**15**	**15.000**

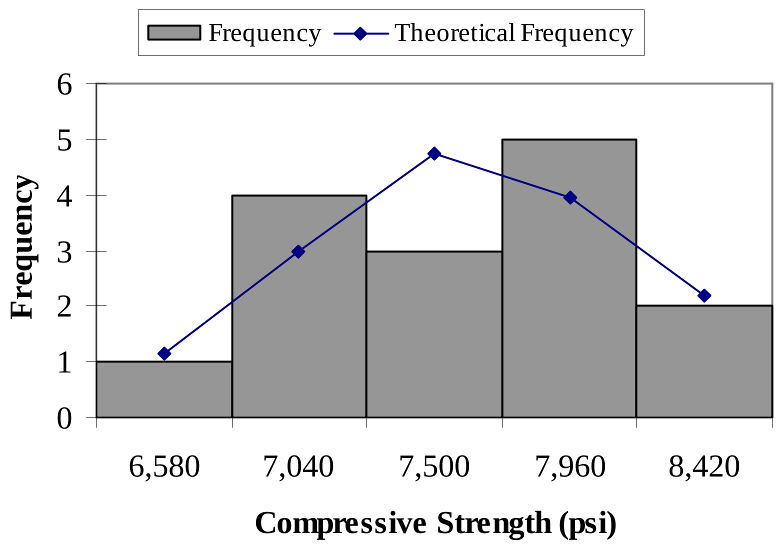


Figure 24
Histogram of Compound B data at the 8,000 psi level

Table 29
Histogram data for Compound C at 8,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
6,266	6,490	1	0.521
6,714	6,938	2	1.965
7,161	7,385	3	4.257
7,609	7,833	4	4.709
8,056	8,280	5	3.548
8,504			
	Sum =	**15**	**15.000**

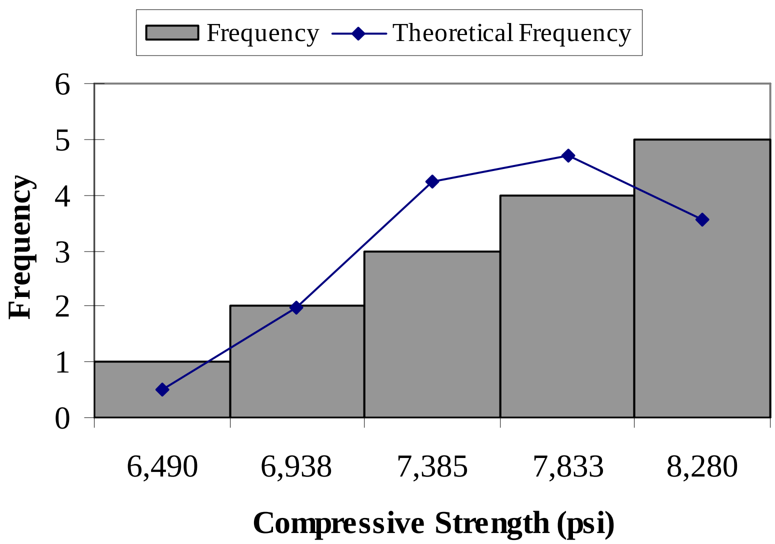


Figure 25
Histogram of Compound C data at the 8,000 psi level

Table 30
Histogram data for Compound D at 8,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
6,879	7,070	3	2.059
7,261	7,453	3	3.819
7,644	7,835	3	4.723
8,026	8,218	5	3.100
8,409	8,600	1	1.298
8,791			
	Sum =	**15**	**15.000**

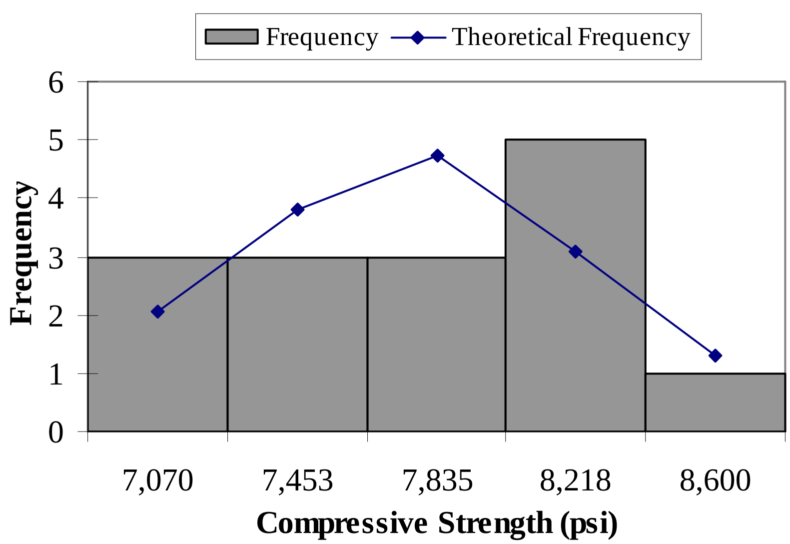


Figure 26
Histogram of Compound D data at the 8,000 psi level

Table 31
Histogram data for unbonded pads at 8,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
6,840	7,010	3	2.241
7,180	7,350	4	3.990
7,520	7,690	2	4.713
7,860	8,030	5	2.925
8,200	8,370	1	1.130
8,540			
	Sum =	**15**	**15.000**

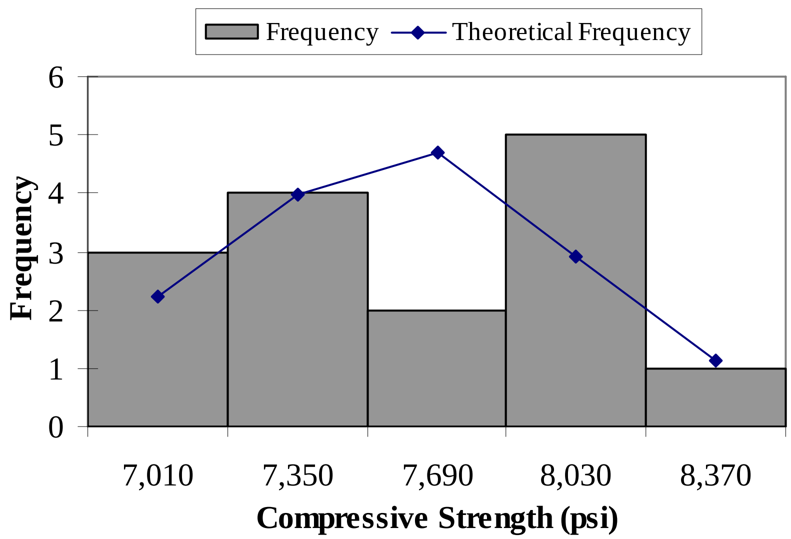


Figure 27
Histogram of unbonded pads data at the 8,000 psi level

Table 32
Histogram data for all data at 10,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
9,603	9,770	2	1.865
9,938	10,105	7	9.077
10,273	10,440	26	23.613
10,608	10,775	27	30.063
10,943	11,110	22	18.750
11,278	11,445	5	5.719
11,613	11,780	1	0.913
11,948			
	Sum =	**90**	**90.000**

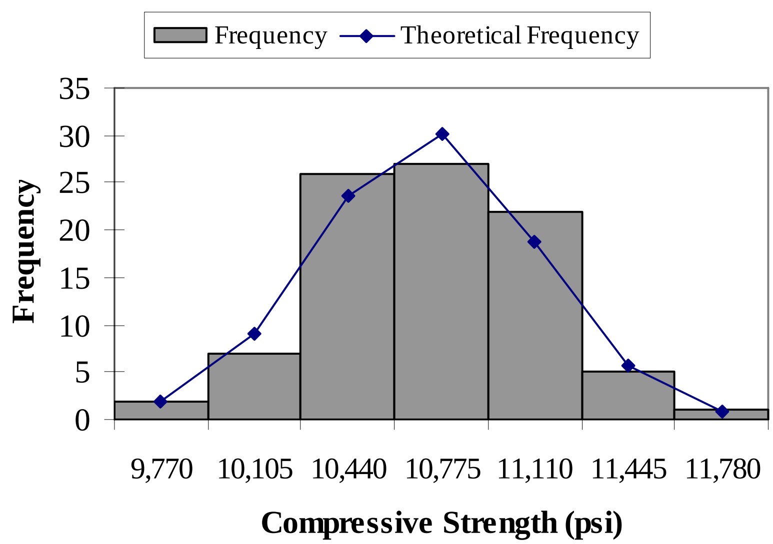


Figure 28
Histogram of all data at the 10,000 psi level

Table 33
Histogram data for ground ends at 10,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
9,631	9,790	1	0.751
9,949	10,108	2	2.567
10,266	10,425	5	4.826
10,584	10,743	4	4.417
10,901	11,060	3	2.439
11,219			
	Sum =	**15**	**15.000**

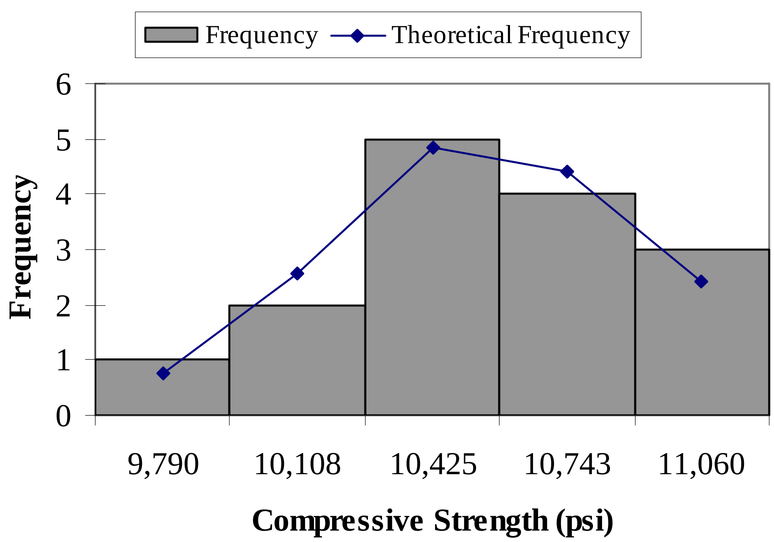


Figure 29
Histogram of ground ends data at the 10,000 psi level

Table 34
Histogram data for Compound A at 10,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
10,228	10,400	3	2.445
10,573	10,745	4	4.466
10,918	11,090	5	4.846
11,263	11,435	2	2.529
11,608	11,780	1	0.714
11,953			
	Sum =	**15**	**15.000**

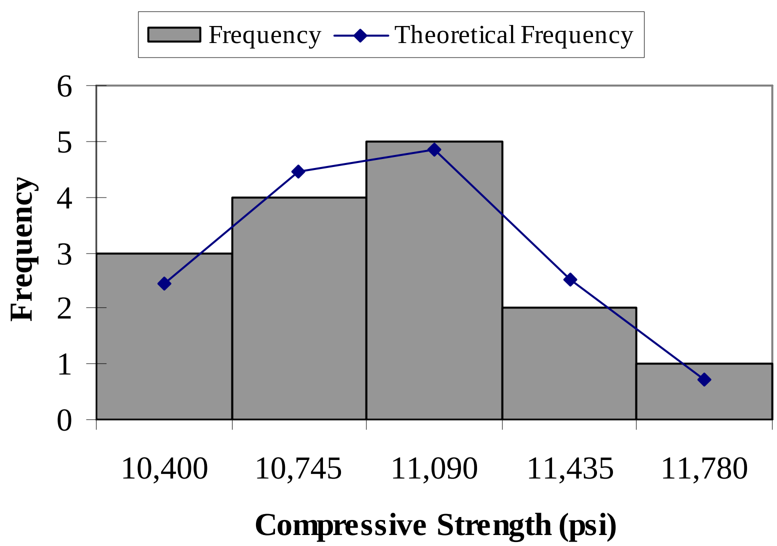


Figure 30
Histogram of Compound A data at the 10,000 psi level

Table 35
Histogram data for Compound B at 10,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
9,544	9,770	1	1.123
9,996	10,223	4	3.791
10,449	10,675	6	5.706
10,901	11,128	3	3.456
11,354	11,580	1	0.924
11,806			
	Sum =	**15**	**15.000**

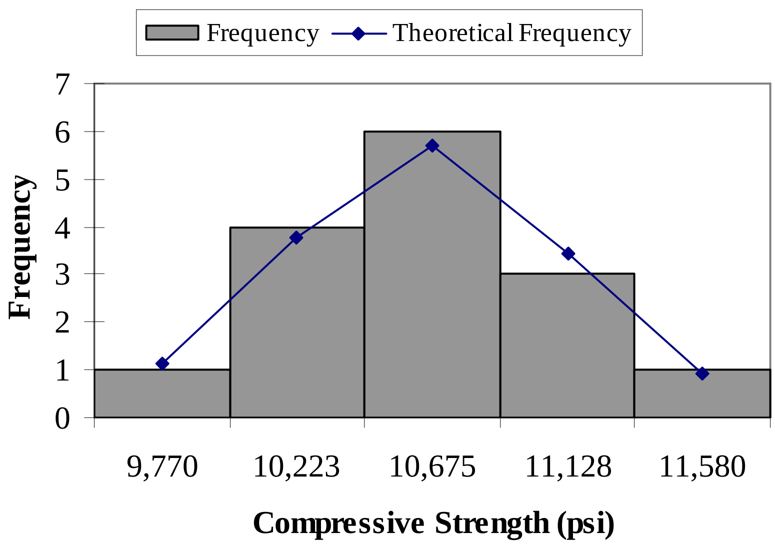


Figure 31
Histogram of Compound B data at the 10,000 psi level

Table 36
Histogram data for Compound C at 10,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
9,853	10,010	1	1.372
10,168	10,325	4	3.431
10,483	10,640	5	5.015
10,798	10,955	3	3.631
11,113	11,270	2	1.551
11,428			
	Sum =	**15**	**15.000**

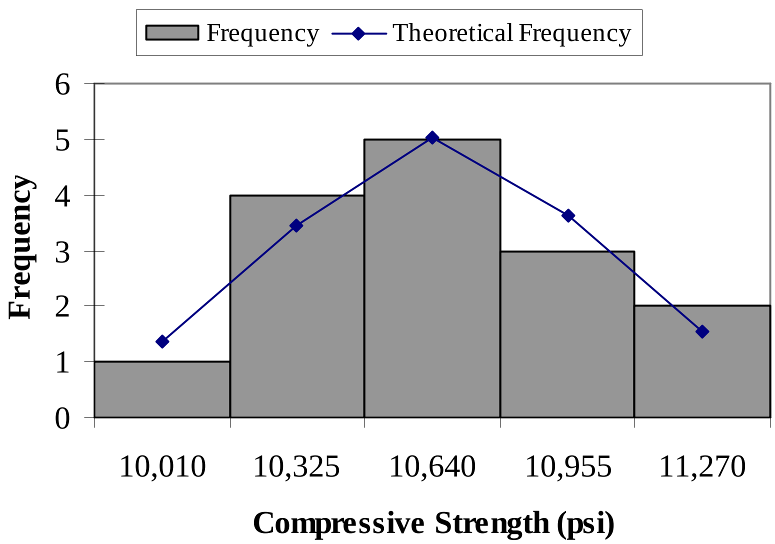


Figure 32
Histogram of Compound C data at the 10,000 psi level

Table 37
Histogram data for Compound D at 10,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
10,185	10,310	4	3.029
10,435	10,560	6	4.573
10,685	10,810	1	4.511
10,935	11,060	3	2.247
11,185	11,310	1	0.640
11,435			
	Sum =	**15**	**15.000**

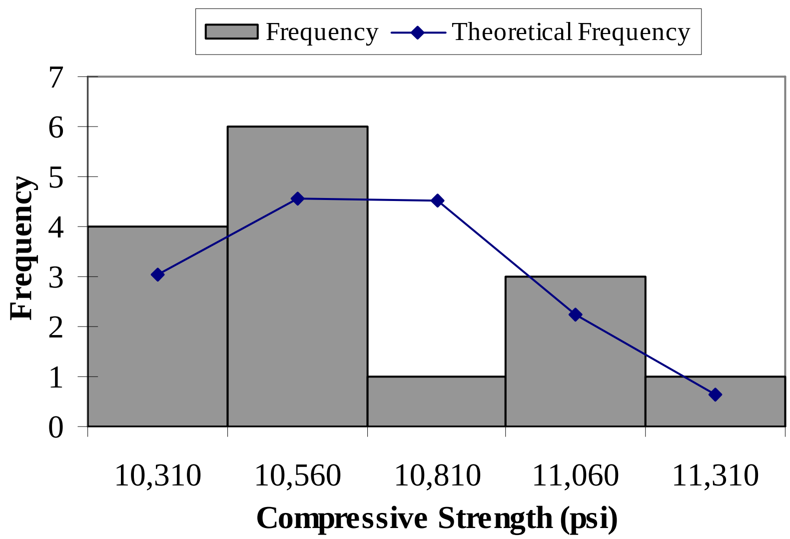


Figure 33
Histogram of Compound D data at the 10,000 psi level

Table 38
Histogram data for unbonded pads at 10,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
10,211	10,340	3	1.954
10,469	10,598	4	3.523
10,726	10,855	2	4.550
10,984	11,113	4	3.293
11,241	11,370	2	1.679
11,499			
	Sum =	**15**	**15.000**

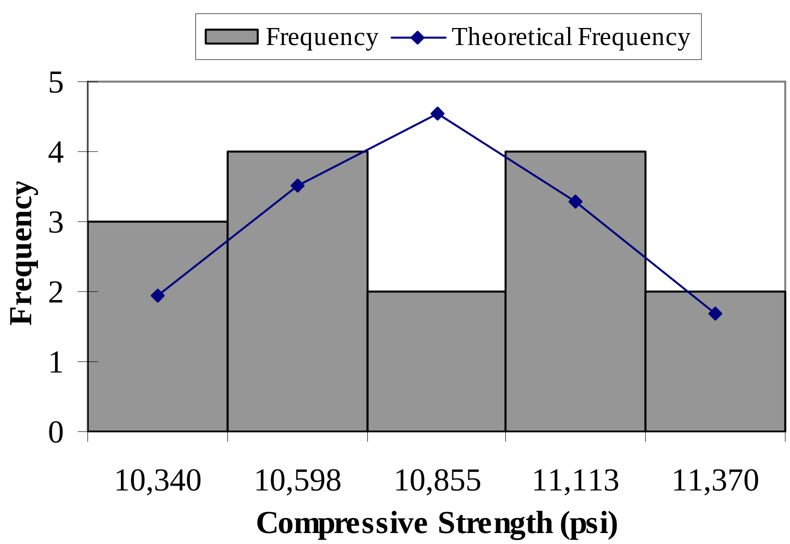


Figure 34
Histogram of unbonded pads data at the 10,000 psi level

Table 39
Histogram data for all data at 12,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
10,476	10,800	2	0.179
11,124	11,448	2	1.962
11,773	12,097	8	10.427
12,421	12,745	18	25.909
13,069	13,393	43	30.208
13,718	14,042	16	16.538
14,366	14,690	1	4.777
15,014			
	Sum =	**90**	**90.000**

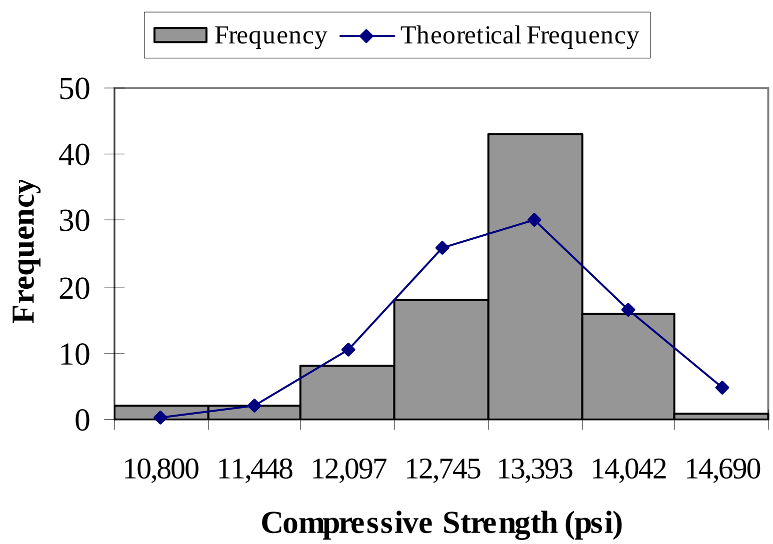


Figure 35
Histogram of all data at the 12,000 psi level

Table 40
Histogram data for ground ends at 12,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
10,373	10,800	1	1.038
11,228	11,655	4	3.280
12,083	12,510	4	5.305
12,938	13,365	4	3.885
13,793	14,220	2	1.492
14,648			
	Sum =	**15**	**15.000**

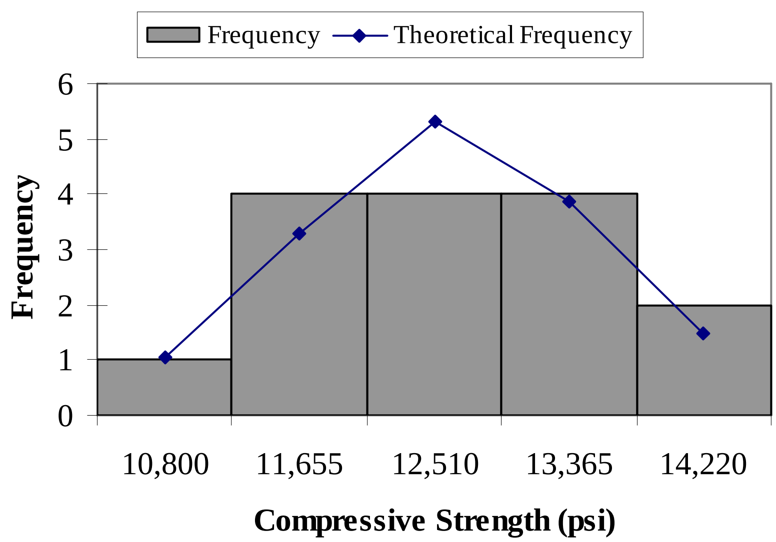


Figure 36
Histogram of ground ends data at the 12,000 psi level

Table 41
Histogram data for Compound A at 12,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
12,739	12,890	3	2.417
13,041	13,193	4	3.726
13,344	13,495	3	4.399
13,646	13,798	3	2.990
13,949	14,100	2	1.469
14,251			
	Sum =	**15**	**15.000**

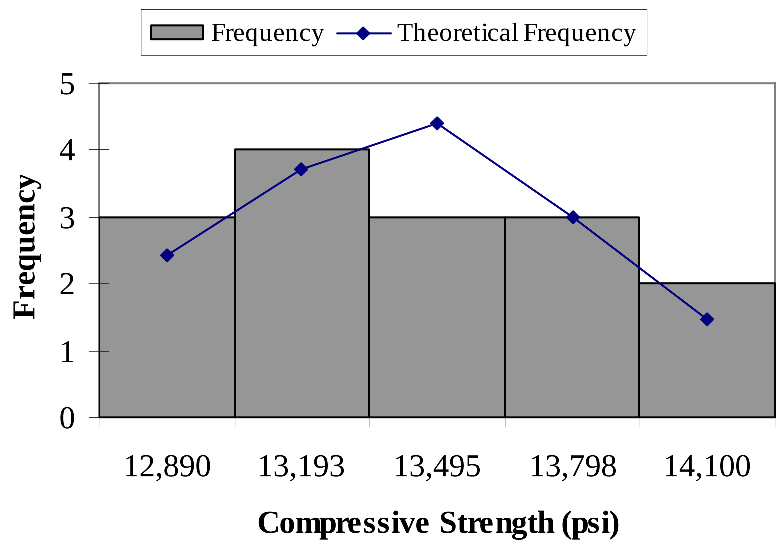


Figure 37
Histogram of Compound A data at the 12,000 psi level

Table 42
Histogram data for Compound B at 12,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
11,569	11,810	2	0.741
12,051	12,293	1	2.305
12,534	12,775	3	4.389
13,016	13,258	6	4.426
13,499	13,740	3	3.139
13,981			
	Sum =	**15**	**15.000**

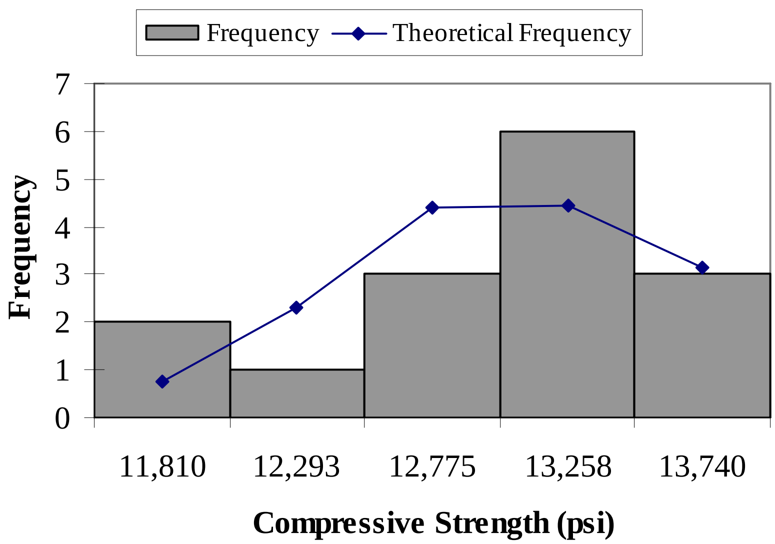


Figure 38
Histogram of Compound B data at the 12,000 psi level

Table 43
Histogram data for Compound C at 12,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
12,760	12,930	1	1.427
13,100	13,270	5	4.214
13,440	13,610	7	5.627
13,780	13,950	1	3.023
14,120	14,290	1	0.708
14,460			
	Sum =	**15**	**15.000**

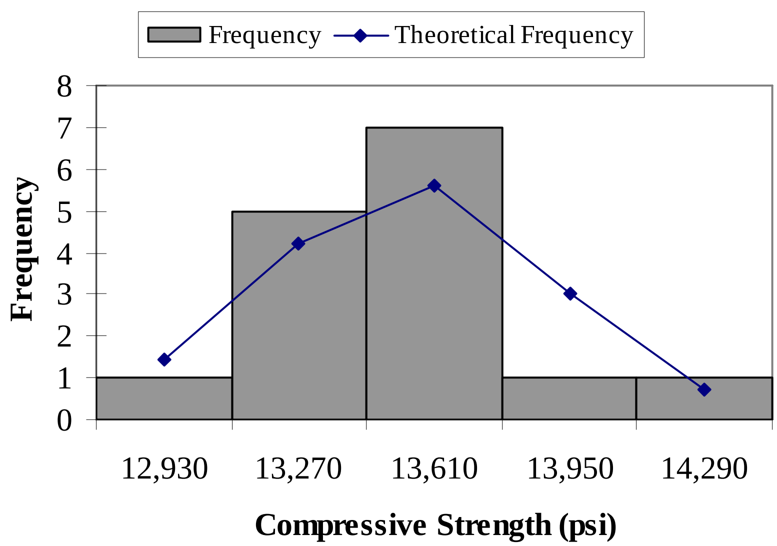


Figure 39
Histogram of Compound C data at the 12,000 psi level

Table 44
Histogram data for Compound D at 12,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
10,566	10,960	1	0.348
11,354	11,748	2	1.893
12,141	12,535	3	4.744
12,929	13,323	8	5.119
13,716	14,110	1	2.896
14,504			
	Sum =	**15**	**15.000**

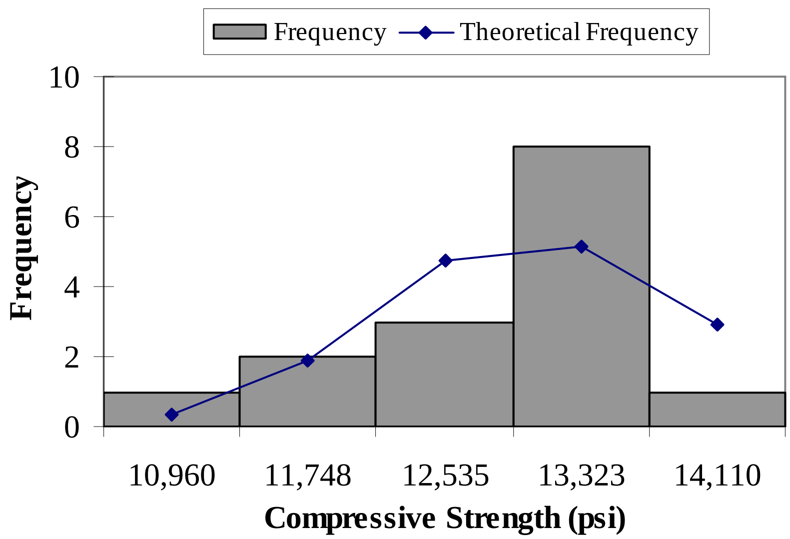


Figure 40
Histogram of Compound D data at the 12,000 psi level

Table 45
Histogram data for unbonded pads at 12,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
12,429	12,680	2	1.791
12,931	13,183	5	3.991
13,434	13,685	3	5.083
13,936	14,188	4	3.099
14,439	14,690	1	1.036
14,941			
	Sum =	**15**	**15.000**

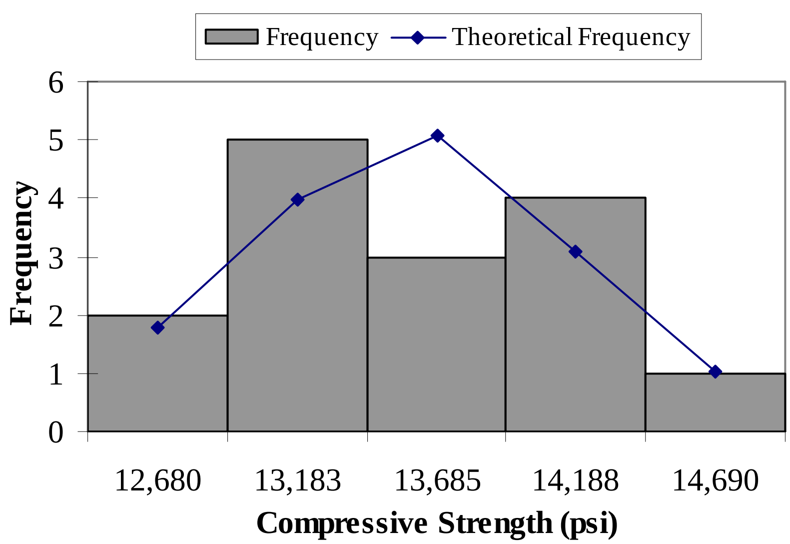


Figure 41
Histogram of unbonded pads data at the 12,000 psi level

Table 46
Histogram data for all data at 12,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
8,525	9,080	1	0.003
9,635	10,190	1	0.129
10,745	11,300	1	1.971
11,855	12,410	8	12.097
12,965	13,520	27	30.130
14,075	14,630	38	30.644
15,185	15,740	14	15.025
16,295			
	Sum =	**90**	**90.000**

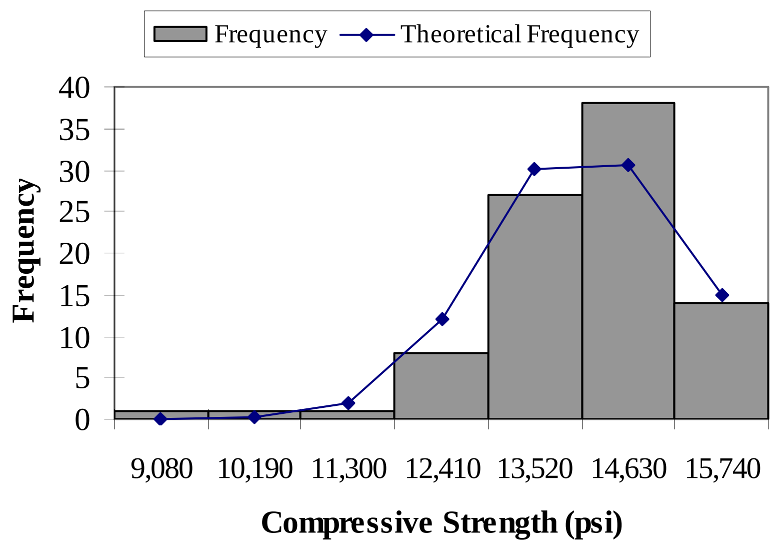


Figure 42
Histogram of all data at the 14,000 psi level

Table 47
Histogram data for ground ends at 14,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
10,058	10,611	1	0.673
11,163	11,716	3	2.235
12,268	12,821	2	4.408
13,373	13,926	6	4.516
14,478	15,031	3	3.169
15,583			
	Sum =	**15**	**15.000**

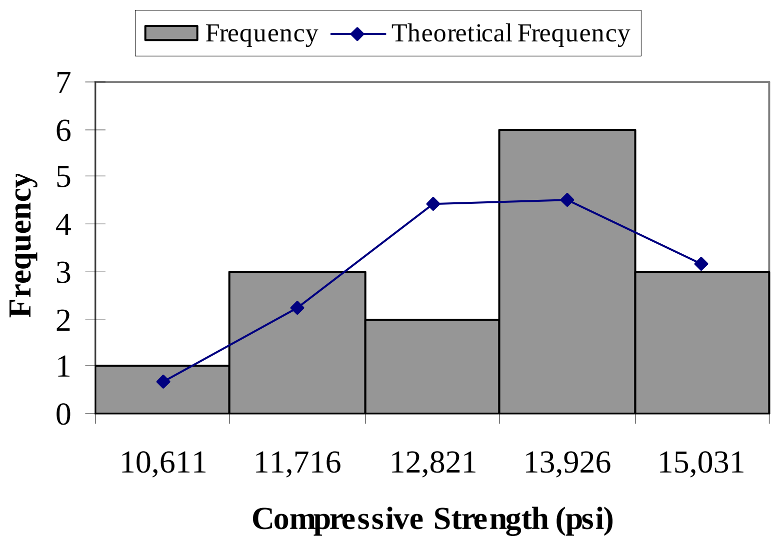


Figure 43
Histogram of ground ends data at the 14,000 psi level

Table 48
Histogram data for Compound A at 14,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
12,468	12,831	2	1.776
13,193	13,556	4	3.530
13,918	14,281	3	4.704
14,643	15,006	5	3.378
15,368	15,731	1	1.611
16,093			
	Sum =	**15**	**15.000**

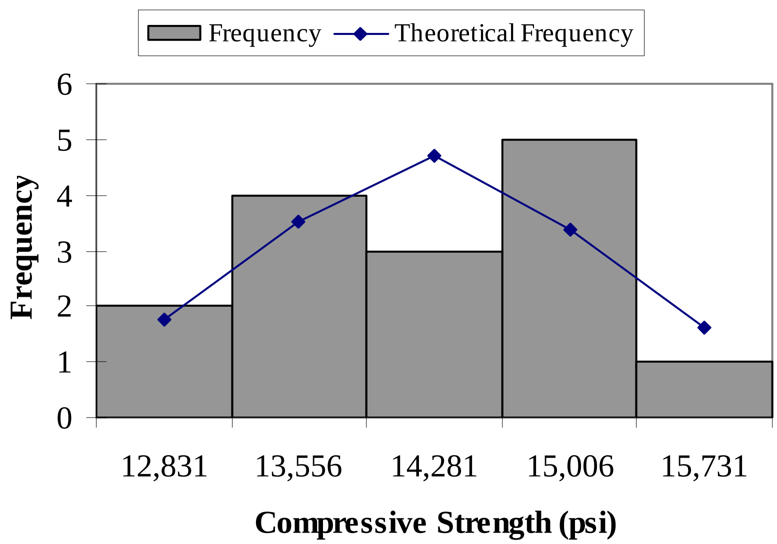


Figure 44
Histogram of Compound A data at the 14,000 psi level

Table 49
Histogram data for Compound B at 14,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
8,309	9,080	1	0.041
9,852	10,623	0	0.562
11,394	12,165	0	2.936
12,937	13,708	7	5.782
14,479	15,250	7	5.679
16,022			
	Sum =	**15**	**15.000**

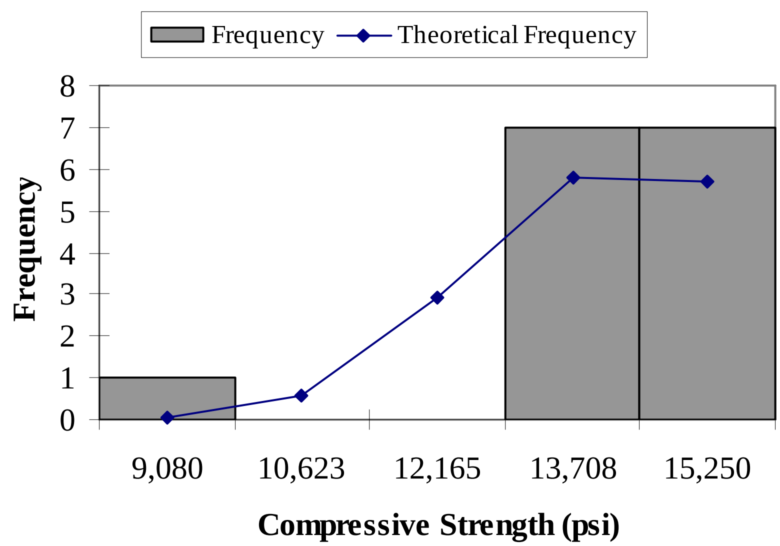


Figure 45
Histogram of Compound B data at the 14,000 psi level

Table 50
Histogram data for Compound C at 14,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
12,193	12,561	2	1.803
12,928	13,296	5	2.713
13,663	14,031	1	3.768
14,398	14,766	1	3.469
15,133	15,501	6	3.247
15,868			
	Sum =	**15**	**15.000**

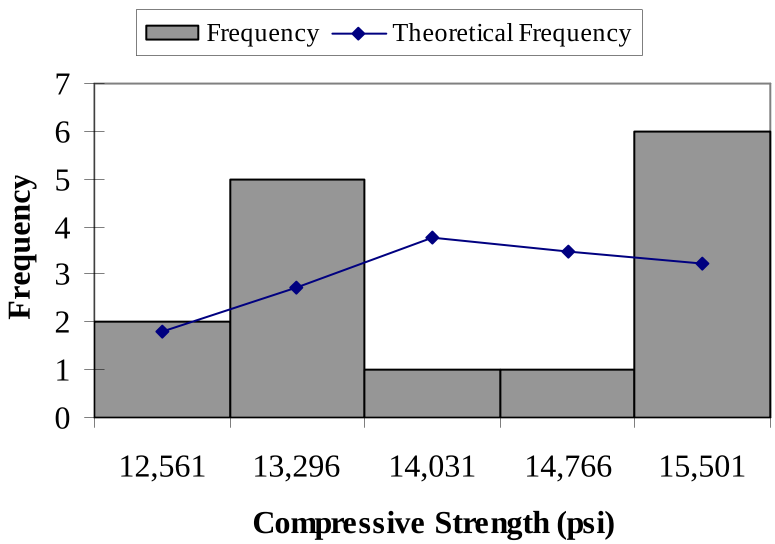


Figure 46
Histogram of Compound C data at the 14,000 psi level

Table 51
Histogram data for Compound D at 14,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
12,303	12,651	2	1.432
12,998	13,346	3	3.168
13,693	14,041	3	4.653
14,388	14,736	5	3.712
15,083	15,431	2	2.036
15,778			
	Sum =	**15**	**15.000**

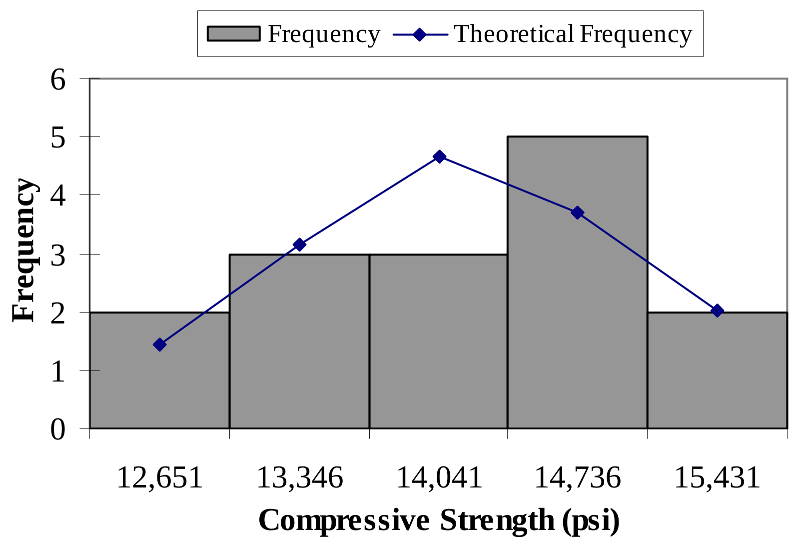


Figure 47
Histogram of Compound D data at the 14,000 psi level

Table 52
Histogram data for unbonded pads at 14,000 psi

Interval Limits	Interval Midpoint	Frequency	Theoretical Frequency
13,198	13,481	3	2.169
13,763	14,046	5	3.794
14,328	14,611	2	4.620
14,893	15,176	4	3.066
15,458	15,741	1	1.350
16,023			
	Sum =	**15**	**15.000**

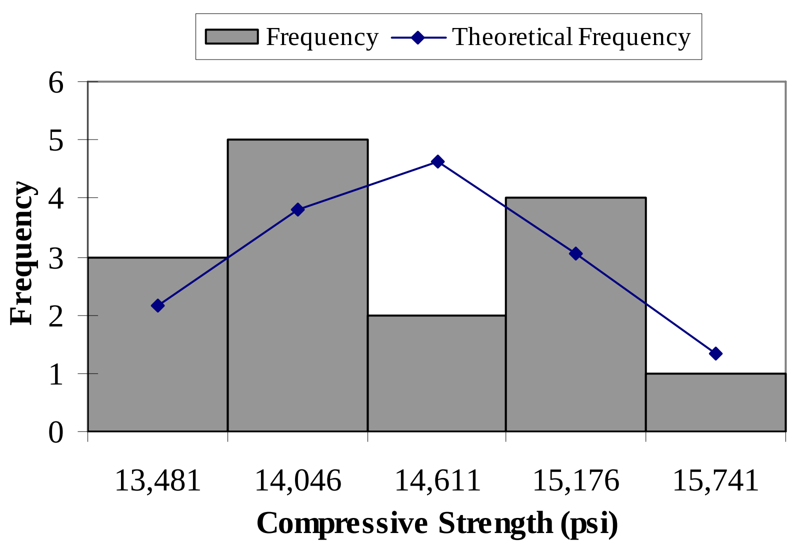


Figure 48
Histogram of unbonded pads data at the 14,000 psi level

Table 53
Goodness of fit checks for 6,000 psi group

End Condition	Number of Intervals	Degrees of Freedom	C-value (from data)	C-value (Chi-Square)	Goodness of Fit Check
All	7	4	2.7748	9.4877	Pass
1	5	2	4.4380	5.9915	Pass
2	5	2	2.4947	5.9915	Pass
3	5	2	2.4996	5.9915	Pass
4	5	2	0.0643	5.9915	Pass
5	5	2	4.4476	5.9915	Pass
6	5	2	4.2395	5.9915	Pass

Table 54
Goodness of fit checks for 8,000 psi group

End Condition	Number of Intervals	Degrees of Freedom	C-value (from data)	C-value (Chi-Square)	Goodness of Fit Check
All	7	4	76.3051	9.4877	Fail
1	5	2	2.4025	5.9915	Pass
2	5	2	8.6365	5.9915	Fail
3	5	2	1.3047	5.9915	Pass
4	5	2	1.5127	5.9915	Pass
5	5	2	2.4671	5.9915	Pass
6	5	2	3.3051	5.9915	Pass

Table 55
Goodness of fit checks for 10,000 psi group

End Condition	Number of Intervals	Degrees of Freedom	C-value (from data)	C-value (Chi-Square)	Goodness of Fit Check
All	7	4	1.7007	9.4877	Pass
1	5	2	0.3819	5.9915	Pass
2	5	2	0.4048	5.9915	Pass
3	5	2	0.1066	5.9915	Pass
4	5	2	0.4345	5.9915	Pass
5	5	2	3.9441	5.9915	Pass
6	5	2	2.2667	5.9915	Pass

Table 56
Goodness of fit checks for 12,000 psi group

End Condition	Number of Intervals	Degrees of Freedom	C-value (from data)	C-value (Chi-Square)	Goodness of Fit Check
All	7	4	29.9574	9.4877	Fail
1	5	2	0.6567	5.9915	Pass
2	5	2	0.7980	5.9915	Pass
3	5	2	3.8826	5.9915	Pass
4	5	2	2.0836	5.9915	Pass
5	5	2	4.7325	5.9915	Pass
6	5	2	1.3961	5.9915	Pass

Table 57
Goodness of fit checks for 14,000 psi group

End Condition	Number of Intervals	Degrees of Freedom	C-value (from data)	C-value (Chi-Square)	Goodness of Fit Check
All	7	4	302.4116	9.4877	Fail
1	5	2	2.2329	5.9915	Pass
2	5	2	1.7179	5.9915	Pass
3	5	2	26.3944	5.9915	Fail
4	5	2	8.0736	5.9915	Fail
5	5	2	1.2695	5.9915	Pass
6	5	2	2.5626	5.9915	Pass